A MANUAL OF RADIOACTIVITY

BY

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COPENHAGEN

AND

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PREFACE TO THE SECOND ENGLISH EDITION

THIS second edition of our *Manual of Radioactivity* is the fourth version of the book. It appeared originally in German (1923), then in English translation (1926), then in a revised German edition (1931), and now it appears again in English. On each of these occasions we have endeavoured to bring the book thoroughly up to date, and to retain its essential characteristics.

Since the publication of the first edition, the need for a general text-book of radioactivity seems to have increased rather than to have diminished. Rutherford's *Radioactive Substances and their Radiations* was published in 1912, and his later work *Radiations from Radioactive Substances*, published jointly with Chadwick and Ellis in 1930, gives a new and detailed treatment of selected chapters on the physical side of the subject only. Meyer and Schweidler's comprehensive volume *Radioaktivität* was last published (2nd edition) in 1927, and we understand that a new edition is not contemplated in the immediate future. Mme P. Curie's extensive treatise *Radioactivité* most nearly approaches in its lay-out the type of book we had in mind when writing the present volume. It appeared in 1935, after her decease, but the treatment of many parts of the book belongs to an earlier date. Hitherto, no other authors appear to have written a text-book in which the attempt is made to treat within reasonable limits the entire field of radioactivity, both in its chemical and in its physical aspects, and in its relation to neighbouring sciences.

The general plan of the book has remained unchanged, but in detail a great deal of it has had to be altered, and several chapters entirely rewritten. We have retained its characteristics as a text-book by deal-ng fully with the fundamental experiments and theories, and by presenting them in as intelligible a manner as possible. In the consideration of the more recent developments we have often had to make use of a more concise treatment, so as to be able more or less to cope with he abundance of the available material. In this respect the essential rpose of our book will have been served if we have been able to give he reader a general survey of modern developments, and direct him to the study of special works of reference and scientific journals. The eferences given at the end of each chapter should prove useful in this onnexion. We have endeavoured as often as possible to direct atten-ion to authoritative books and to reviews in scientific periodicals; ndividual papers have only been cited in so far as they justify the nclusion of particular statements in the text, and the absence of eferences to other papers in no way indicates an expression of opinion on their value, for there are obvious practical limitations to the number of references that can be included in a book of this kind. If we were to attempt to give a complete list of references even for the more recent work, it would be necessary to supplement each chapter by several pages of references, for the amount of published work has grown enormously in recent years, especially in the field of radioactivity. From information that we have received from Professor St. Meyer, some 1,200 papers on the subject appeared during the year 1936 alone.

Uncertainty in regard to the values of the fundamental constants (electron charge, Loschmidt's number, etc.) gave rise to some difficulty. In view of this uncertainty we have, when permissible, made use of approximate numerical values in the text, and in a table in the Appendix we have listed those which, in the present state of knowledge, are to be regarded as the most probable exact values of the constants.

It is our pleasant duty to record our thanks to Drs. O. Frisch and J. C. Jacobsen (Copenhagen) for their critical perusal of parts of the manuscript, to Professor Stefan Meyer (Vienna) for kindly looking over the proofs and for numerous valuable suggestions for improving the text, and above all to Dr. R. W. Lawson (Sheffield) for his very careful translation and invaluable assistance in various ways during the preparation of this edition of our book.

During the printing of this edition the announcement was made of the lamented death of Lord Rutherford. To him, more than to any one else, the scientific world is indebted for the development of the science of Radioactivity throughout its history. For our own part we should like to take this opportunity of expressing our deep feeling of reverence and gratitude to the late Lord Rutherford for the manifold inspiration and encouragement he gave us during the course of the last twenty-five years.

March 1938.

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FROM THE PREFACE TO THE FIRST GERMAN EDITION

THE purpose of the present volume is sufficiently indicated by its title; it is intended to be a text-book of radioactivity.

There already exist several exhaustive works on radiology for the advanced student and the research worker, and detailed monographs on certain branches of the subject have been published from time to time. Nevertheless, it has been our experience, and doubtless many of our colleagues have been faced with the same difficulty, that students—in physics, chemistry, and medicine—invariably ask the question as to which is the most suitable book from which to get an insight into the science of radioactivity at first hand, and without assuming an elementary knowledge of the subject. Owing to the wide range of the subject, this is by no means an easy question to answer.

In view of this fact, we have attempted to select and arrange the subject-matter so as to give prominence to the didactic points of view, somewhat in the same manner as has long been done in every text-book on the related sciences of physics and chemistry. Whereas in the early days of radioactive research, before the relation between the numerous remarkable observations was recognized, it was convenient to make use of the historical development of the subject as an introduction to the new science, we believe that the time is now opportune for completely separating the didactic from the historical development of radioactivity. Our meaning will be clear if we remind the reader that a text-book of chemistry does not begin with a description of the misconceptions of the alchemists, but rather with the much more instructive experiments of a quantitative nature on the composition of water, etc., in spite of the fact that they belong to a much later period and are more difficult to carry out. At the same time we do not consider the historical development to be without interest, and students who are already familiar with e elements of the subject will find in the concluding chapter a résumé progress in radioactive research from its inception onwards, together with an indication of the part played in that work by the various research laboratories.

We have only introduced the principles of the methods of measurement used in radioactivity, and not the practical manipulative instructions; here again we find justification in the accredited procedure of text-books on physics and chemistry, which leave technical laboratory details to the treatises on practical physics, or analytical and preparative chemistry.

G. H.
F. A. P.

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INTRODUCTION

1. Fundamental Experiments

The science of radioactivity derives its name from the chemical element radium, which was discovered in the year 1898, and it is mainly with this substance that the unique phenomena have been observed, the study of which forms the basis of this new science. Radium is obtained by separating in the form of chloride the slight traces of barium contained in uranium minerals, and then subjecting this to fractional crystallization. Under such treatment, the more difficultly soluble fractions become richer in the chloride of radium, which in this manner can finally be obtained in the chemically pure state.† From the chemical viewpoint the salts of radium (chloride, bromide, carbonate, sulphate, etc.) and metallic radium bear a strong resemblance to the corresponding compounds of barium and to metallic barium respectively, but they differ from this and from practically all other chemical elements by virtue of certain special properties. We shall discuss the most important of the experiments which show this peculiarity of radium, but at this stage we shall refrain from the discussion of the experimental difficulties which some of them offer. In these experiments we may use a few centigrams of radium chloride, contained in a small glass tube with sealed ends.

(1) If the glass tube be laid for a few seconds on a photographic plate, then after development the plate is found to be strongly blackened where the tube was situated; at greater distances the effect is less marked.

(2) A screen coated with barium platino-cyanide, such as is used in detecting the presence of X-rays, is also found to become luminous when the tube containing radium is brought near it.

(3) A charged electroscope loses its charge when the tube is situated near it.

(4) Very small quantities of two different gases, helium and radon, gradually accumulate within the tube, and can be detected by the methods of micro-gas analysis.

(5) If part of the glass tube be exceedingly thin, but nevertheless quite airtight, the appearance of the gas helium can also be observed outside of the tube.

(6) The tube has always a slightly higher temperature than its surroundings.

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† Further details of the mode of preparation are contained in Chap. XXII.

In the explanation of these remarkable properties we are especially aided by experiment (4). By means of the most accurate chemical analysis we are able to detect in the tube initially only the two elements radium and chlorine in the form of the solid compound $RaCl_2$. After the lapse of a few days or weeks, however, the tube contains an exceedingly small quantity of a gaseous mixture, the spectroscopic examination of which, in addition to helium, reveals the presence of an element previously unknown, and called radon. Owing to the characteristic nature of its spectrum, and because of its inability to take part in chemical reactions, this element, like helium, must be included among the rare gases. Two new elements have thus been derived from radium chloride, and since the same results can be obtained by using radium bromide, radium carbonate, etc., and metallic radium, we are led to the conclusion that it is the element radium that has been transformed into the other two chemical elements.

A quantitative investigation supplies us with a clue to the manner and nature of this transformation. If we were to seal off 1·3138 gm. $RaCl_2$ (containing 1·000 gm. of the element radium) in an evacuated tube, we should be able to establish by the methods of micro-gas analysis that after four days 0·33 mm.^{3} of radon have been produced (measured at 760 mm. pressure and at 0° C.), whereas the amount after eight days would be 0·50 mm.^{3}, and after thirty days 0·65 mm.^{3} Moreover, we should find that no matter how long we wait, even after several years, this last value would not be exceeded. In the case of helium, on the other hand, we should find that if we neglect the growth during the first few days, the accumulation of helium would be proportional to the time that had elapsed since the tube was sealed off, so that after one year we should find approximately 172 mm.^{3} of helium, after two years twice this amount, and so on.†

This difference in the behaviour of helium and radon must find its explanation in the nature of the two gases. In order to investigate this point we shall suppose them to be collected separately, and observe their behaviour during the course of an extended period of time. The helium is found to remain unaltered, and no matter how long we keep it, the volume remains constant. The behaviour of the radon, however, is quite different. Initially it was completely free from helium, but after the course of a few days we are again able to detect the presence of this gas in the radon, whereas the amount of radon constantly diminishes. After the lapse of four days only one-half of it is left, after eight days only about one-quarter, and after one month only about one-thousandth of the original quantity of radon is left. This process is accompanied by another surprising phenomenon, which is of particular importance in the interpretation of the process: a deposit of lead is found to form on the walls of the vessel in which the radon has been stored. The quantity of lead formed bears a simple relation to the amount of radon that has disappeared; in place of each atom of the latter an atom of lead makes its appearance, and hence the quantity of lead increases during the first four days to one-half of its maximum amount. After one month the amount of lead remains practically constant.† Furthermore, it can be shown that the tube containing radon gives rise to all the phenomena described under experiments (1), (2), (3), (5), and (6), which we were able to observe with the tube containing radium.

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† The above relation does not hold quite accurately, owing to the fact that in the course of several months an appreciable quantity of polonium will have been formed, and the generation of helium from this source must also be taken into account.

2. The Hypothesis of Atomic Disintegration

Without exception it has been found possible to explain all the above-mentioned observations and experiments by means of a theory which also embraces many other related phenomena not touched on here, and which rendered possible the correct prediction of phenomena not yet discovered. The theory is based on a single hypothesis, in principle quite novel, namely, the assumption of the disintegration of the chemical atoms.

Before the discovery of the radioactive elements it had been possible to attribute the whole of the phenomena in chemistry and physics to the behaviour of the atoms and of their association in the form of molecules. In spite of numerous experiments, science had never succeeded in establishing the transformation of one chemical element into another, and since we regard the atoms as the carriers of the properties of elements, we were forced to the conclusion that chemical atoms remain unaltered under all circumstances. This conception does not stand in contradiction to the fact that, in many processes such as the emission of light, ionization, and especially the formation of chemical compounds, certain properties of the atoms disappear, and others take their place. We need only assume that the essential nature of the atom is maintained, and that only relatively minor changes take place, which can always be made retrogressive.‡

Since the new elements helium and radon are formed from radium, we must assume in this case that atoms of helium and of radon are produced from the atoms of radium. Here we are confronted with a disintegration of the radium atom, and this process is not reversible. In spite of experiments on these lines, it has never been possible to detect the formation of radium from helium and radon. This property of disintegration is associated not only with radium, but also with radon, as mentioned above, which is transformed in its turn into other elements. The same feature characterizes a large number of other radioactive substances, with which we shall become acquainted later on. Previously established conceptions in chemistry and physics were of no avail in the face of these facts, and it became necessary to develop a new science, the science of Radioactivity.

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† Later on we shall deal with the properties of the lead so produced. It is called radium D.

‡ We shall have occasion in what follows to discuss what we have to understand by the 'essential nature of the atom', in the light of more recent theory.

Like the word radium, the term radioactive was chosen in this new science because the first phenomenon to receive attention was the emission of particularly characteristic rays (*radius* = ray) by such substances; not until later was it noticed that these rays solely represent phenomena accompanying atomic disintegration, and for this reason we now define a substance as being radioactive when the atoms of which it is composed disintegrate spontaneously, and regardless of whether or not the emission of rays can readily be detected in the process.

The phenomena that were mentioned in connexion with our basal experiments (1) to (6) all represent effects produced by these rays; we shall be made familiar with the nature of the rays in later chapters specially devoted to this aspect of the subject. At this stage it will suffice to mention that they are not only useful for the qualitative detection of radioactive substances, but they can also be utilized with especial advantage in the quantitative measurement of such substances. The intensity of each type of ray is simply proportional to the available quantity of the substance emitting it. Instead of the above-mentioned chemical or gas-analytical method of detection of the quantity of a radio-element, which is in practice a very irksome business, we almost always make use of the measurement of its radiation in the determination of the amount present. For this reason it is imperative that we should have an accurate knowledge of the rays, and of the methods used in their measurement.

3. The Rays emitted by Radioactive Substances

In order to render this section more readily intelligible, it will be of advantage to call to mind the different theories that have been formulated as to the nature of rays of light, and other types of rays familiar to physicists. Whereas Newton assumed that rays of light consist of a swarm of very quickly moving material particles, Huyghens's conception was that we are not dealing with the propagation of material constituents, but with that of a state of motion. According to his theory, which, after much tedious discussion and numerous experiments, was found to be more fruitful in the case of light than Newton's theory, we have to regard a ray of light as consisting of the propagation of a state of vibration in the aether. Later, the same two alternatives presented themselves in the case of the cathode rays and X-rays. Here again both modes of explanation found distinguished protagonists, until the emission theory held the field for cathode rays, and the wave theory for X-rays.

For the radioactive substances it is not possible to come to a simple decision one way or the other, for here we meet with both types of rays, some of them of a material nature and others resembling light. The α- and β-rays are corpuscular, whereas the γ-rays, like the closely related X-rays, are simply a form of light of very short wave-length. But it should be mentioned that the developments of theoretical and of experimental physics in recent years have led to the conclusion that a rigid differentiation between the two types of rays is not possible. Even an apparently so typical corpuscular radiation as that of the α-particles, which when collected yield the gas helium, can be regarded in other respects as a wave radiation capable of interference. In a preliminary survey of the subject of the rays from radioactive substances, it is however advisable to retain the differentiation previously given.

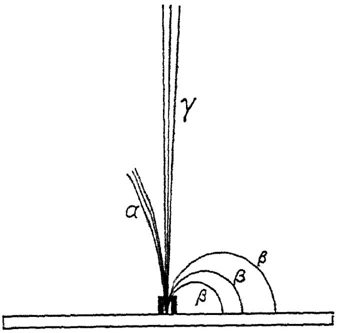

FIG. 1. Action of a Magnetic Field on α-, β-, and γ-Rays.

It has been mentioned that even before the discovery of radium we were familiar with types of rays that were regarded as corpuscular in nature, in contrast to the rays of light. Thus the cathode rays, which result from the application of a high voltage across a highly evacuated tube, consist of a swarm of particles of negative electricity, called electrons; and in the same tube we can detect particles flying in the opposite direction, i.e. towards the cathode, and these are called positive rays. According to the gas contained in the tube (oxygen, carbon dioxide, mercury, etc.), these positive rays consist of molecules and atoms of different chemical elements and compounds, associated with positive electrical charges. β-rays are identical in nature with the cathode rays, whereas the α-rays show a marked similarity to positive rays.

Our knowledge of the nature of the rays emitted by radium was obtained from experiments on their deflexion and absorption. The accompanying diagram (Fig. 1) shows schematically the action of a strong magnet on a pencil of α-, β-, and γ-rays emitted in a rectilinear direction from a narrow opening. In this diagram the magnetic field is supposed to be directed perpendicularly to the plane of the paper, with the north pole of the magnet above that plane. The α-rays are slightly deflected to the left, whilst the β-rays suffer a much greater deflexion to the right. If the magnetic field is sufficiently strong, the β-rays are bent into complete circles, but the γ-rays are wholly uninfluenced by the magnetic field. From the direction of the deflexion we are able to determine whether the charge on the particles is positive or negative, and from the magnitude of the deflexion, combined with similar deflexion experiments in an electric field, we can determine the magnitude of the specific charge (e/m) and the velocity of the α- and β-particles.

Another fundamental experiment consists in testing the absorption of the rays, i.e. the diminution of their intensity after they have passed through matter, whether this be in the gaseous, liquid, or solid state. Whereas the γ-rays are only slightly weakened in intensity by the introduction in their path of an aluminium plate 5 mm. thick, the α-rays are completely, and the β-rays almost completely absorbed by the plate. On the other hand, a thin sheet of paper or of aluminium of thickness 0·1 mm. is insufficient to cut off the β-rays, but it is wholly effective in preventing the passage of α-rays. In this way then we have, together with magnetic and electric deflexion experiments, a simple means of separating the different types of rays from each other.

We must now familiarize ourselves with the methods of measuring the intensity of the rays from radioactive substances. Since these methods are based almost exclusively on the determination of the electrical conductivity imparted to gases by the rays, it will be profitable at this stage to give an account of the mechanism of the conduction of electricity in gases.

4. Conduction of Electricity in Gases

By way of illustration we shall proceed from the more generally familiar conduction of electricity in liquids. As detailed in every text-book of chemistry or physics, pure water is practically a non-conductor of electricity; but when we introduce an electrolyte such as hydrochloric acid into it, the liquid acquires the ability to conduct an electric current. Moreover, it can be shown that at the same time there occurs a wandering of H-atoms towards the cathode, and of Cl-atoms towards the anode. From this it follows that the H-atoms are positively charged, whilst the Cl-atoms possess a negative charge, and that the passage of the current consists in a transport of these charged particles.

Furthermore, we can readily calculate the magnitude of the charge of these particles, which are called ions (*ion* = wanderer). According to Faraday's second law, the same quantity of electricity is always necessary in order to deposit one gram-equivalent of a substance, this quantity amounting to 96,500 coulombs. With this quantity of electricity we can, for instance, separate 1·008 gm. of hydrogen or $\frac{16}{2} = 8$ gm. of oxygen. Now we know that 1·008 gm. of hydrogen contains $6{\cdot}0 \times 10^{23}$ atoms, and hence every hydrogen ion bears a charge of

$$\frac{96500}{6{\cdot}0 \times 10^{23}} = 1{\cdot}6 \times 10^{-19}$$

coulombs. Such small quantities of electricity are advantageously expressed in terms of another system of units; since 1 coulomb $= 3 \times 10^9$ electrostatic units, it follows that the charge borne by a monovalent ion is $1{\cdot}6 \times 10^{-19} \times 3 \times 10^9 = 4{\cdot}8 \times 10^{-10}$ e.s.u. A divalent ion requires 96,500 coulombs to deposit half a gram-atom, and since this half gram-atom only contains half the number of atoms contained in a gram-atom, we see that in this case each individual ion carries a double charge $= 2 \times 4{\cdot}8 \times 10^{-10}$ e.s.u., and that every trivalent ion carries a treble charge, and so on.

The fact that the charge of an ion is either $4{\cdot}8 \times 10^{-10}$ e.s.u. or a whole multiple of that value leads us to the atomistic conception of electricity; a smaller quantity of electricity than this elementary charge e has never been observed. As is well known, for these negative 'quanta' of electricity it has been possible to establish their independent existence, free from matter; they invariably possess the same electrical charge, independently of the substance from which they have been derived. They are called electrons, and we shall meet with them again in the β-rays from radioactive substances.

We shall use this well-known conception of the conduction of electricity in liquids as a starting-point in the elucidation of the conduction of electricity in gases, with which the following observations have been made.

Charged bodies that are in contact with a gas gradually lose their charge. Coulomb thought that the gas molecules become charged by contact, and then hand over their charges to the walls of the vessel. But this interpretation stands in contradiction to the observation that the loss of charge is greater the larger the containing vessel. From this we may conclude that the discharge is brought about by the aid of particles which are present in limited number in the vessel, and which cannot be replaced after they have been used up. This conclusion is confirmed by experiments with gases, the conductivity of which is greatly increased by allowing them to bubble through water, by bringing them into contact with flames, electric arcs, glowing metals, or phosphorus, or by subjecting them to the influence of ultra-violet light, cathode rays, positive rays, X-rays, or the rays from radium. The enhanced conductivity vanishes of its own accord in the course of time, but with especial rapidity when the gases are passed through glass wool, through narrow metal tubes, or through an electric field. Thus the conductivity must be attributed to particles that can be filtered from the gases and which are electrically charged. Since the gas as a whole shows no electric charge, equal numbers of positive and negative particles must be present. These particles are also called *ions*, and the production of conductivity is called the *ionization* of the gas.

Thus, just as in salt solutions, the conduction of electricity in gases is brought about by the agency of electrically charged particles. Nevertheless, there are important differences between the two phenomena. In particular, we must note here one such difference, and that is the relation between the applied potential and the current strength. As is well known, this relation is given within wide limits for electrolytically conducting liquids by Ohm's law, $I = V/R$, just as with metallic conductors, i.e. the current is proportional to the potential when the resistance is constant. We explain this relation by saying that with twice the potential the force acting on the ions is twice as large, and hence the velocity they acquire in the resisting medium is also doubled, so that the current or the quantity of electricity transported in unit time will also have double its previous value. This proportionality between current and potential can be graphically represented by means of a straight line passing through the origin. With gases ionized by X-rays or the rays from radium, on the other hand, this simple relation only maintains for the initial part of the curve (region of Ohmic current), and when the potential is sufficiently high a maximum current value is attained, and this cannot under normal circumstances be exceeded.

These conditions can be made clear by graphical means, as shown in Fig. 2.

When we ionize a gas by means of a radioactive preparation of given strength and gradually raise the potential applied to the gas space, the current rises at first quickly, and later slowly, as shown by curve A. The current is constant for potentials above a certain value. With a stronger radioactive preparation the curve has a similar form, but attains a higher constant value (curve B). Thus whereas for small potentials the current strength depends both on the applied potential and on the strength of the radioactive preparation, it is a function only of the strength of the preparation once a certain high value of the potential has been reached or exceeded. We see, then, that under these conditions the current strength can be used as a measure of the strength of the radioactive preparation. This maximum value of the current is called the *saturation current*.

These results are explained in the following manner. Both in the case of electrolytic and of gaseous ions a fraction of the ions disappears by virtue of the recombination of oppositely charged ions to form neutral particles, even in the absence of an electric field. Thus in the aqueous solution of a weak electrolyte in the stationary state a condition of dynamic equilibrium exists between the molecules that are split up into ions in each second of time by the dissociating action of the water, and the ions that reunite during the same interval to form uncharged molecules. Likewise, a state of dynamic equilibrium is also maintained between the gas molecules broken up into ions by the action of the X-rays, and the ions of the gas that combine to form uncharged particles.†

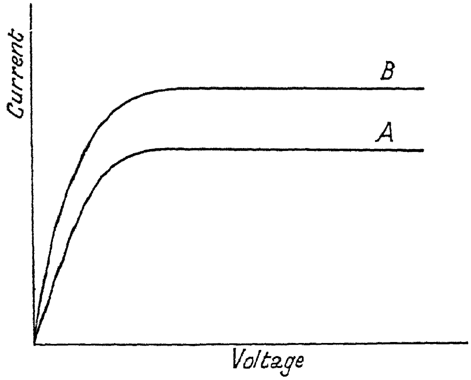

Fig. 2. Attainment of Saturation Current.

When an electric field is applied, the positive ions wander to the cathode and the negative ions to the anode, and if the field is of sufficient strength, the transport can take place so quickly that the ions no longer have an opportunity of losing their charges by recombination, and they all give up their charges to the electrodes. Now with electrolytes this case cannot be realized; first, because the number of ions is very large, and secondly, because they can only be transported slowly towards the electrodes owing to the resistance offered by the water. Thus, even when a strong field is applied, the equilibrium between separation and recombination of the ions is not appreciably disturbed.

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† The velocity of recombination of oppositely charged ions to form uncharged particles is proportional to the product of the concentrations of the positive and negative ions. Hence the number dn of the ions that combine per unit of volume in the time dt is given by the expression

$$dn/dt = \alpha n_1 n_2.$$

The constant α is called the *coefficient of recombination*. Since the same numbers of positive and negative ions are formed per unit of time, we have $n_1 = n_2$, and the above expression reduces to

$$dn/dt = \alpha n^2.$$

On the other hand, in gases ionized by means of X-rays or the rays from radium the number of ions is much smaller, and their mobility much greater.† In this case, by increasing the potential, it is actually possible to remove to the electrodes all the ions produced during a definite time by the action of the ionizing agent, or in other words, all the ions take part in the transport of the current. As soon as this condition is fulfilled, a further increase of the potential difference is no longer able to bring about an increase in the current, for of course only a definite number of ions is being produced per unit of time. If the ionizing action is increased, the value of the current will also rise, since there are now more ions available. Thus the current is now a measure of the ionizing action, and, within certain limits, it is independent of the potential. Hence, if we wish to measure exactly the ionizing action of a radioactive preparation, it is desirable to make use of the saturation current.‡

The first part of the curves in Fig. 2, the region of Ohmic current, corresponds to the conditions with electrolytes, but the later part of the curves (incomplete saturation and the saturation current) is not attainable in the case of electrolytes.

At first sight it seems a surprising phenomenon that the saturation current becomes greater when the plate electrodes are farther apart; but the explanation of this is also given directly by the theory. If the ionization takes place uniformly throughout the gas, the number of particles produced per unit of time between the electrodes will be larger the greater the distance between the plates, and hence the current may also be larger. In contrast with this we know that for metallic conductors and electrolytes the strength of the current diminishes as we increase the distance between the electrodes.

In view of its practical importance we have dealt in some detail with the dependence of conductivity on the potential. But there are still other important differences between electrolytic ions and gas ions. In the first place, for the latter ions the close relationship of the charge and the chemical nature of the substance is absent. In electrolysis it is well known that hydrogen always carries one positive charge, and oxygen always carries two negative charges, and so on; but the gas ions in hydrogen and in oxygen carry exactly the same charges. Moreover, whilst we meet with ionized atoms in the solutions of most substances, the gas ions of the same substances generally consist of ionized molecules. In electrolysis all the ions have similar dimensions, even though, in consequence of stronger or weaker hydration, somewhat considerable differences in their magnitude (and corresponding mobility) do occur; but in the case of gas ions the multiplicity is much greater, and at the present time we can visualize the following picture of the process of ionization in gases.

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† Whereas the ion content of a normal solution of a strong electrolyte amounts to 6×10^{20} per c.c., it rarely exceeds 10^8 per c.c. in a gas, even with the strongest ionization by X-rays or similar ionizing agency. The mobility of ordinary gas ions in oxygen is about 1 to 2 cm./sec. per volt/cm., and in hydrogen it even reaches the value of 7 to 8, whereas the mobility of most electrolytic ions (Cl, K, etc.) in water only amounts to 7×10^{-4}, and even that of the H-ion does not exceed 3×10^{-3}. Both factors, namely, the smaller number and the greater mobility of the ions, are favourable to the attainment of the saturation current in the case of gases. The conductivity is reduced by the first factor, and increased by the second, but in much lesser degree, so that the conductivity even in hydrogen can only reach a value corresponding to that of an acid solution of strength about 10^{-10} N.

‡ The attainment of the saturation current should be aimed at in all such measurements. It is, of course, also possible to compare the strengths of preparations by using currents below saturation, provided that the conditions of experiment are kept quite constant, and in many measurements we must for practical reasons sacrifice the attainment of complete saturation. Particularly with α-rays, which produce many more ions per centimetre of their path than β-rays (see pp. 43 and 67), it is often not possible to reach saturation.

As a result of the collisions of gas molecules with the electrons of cathode or β-rays (or even secondary electrons that have been liberated by X-rays, γ-rays, or ultra-violet light), a neutral particle parts with an electron. As a result of this a positive ion of atomic dimensions is simultaneously produced. At low pressure or at high temperature these ions exist as free ions in the gas, but otherwise uncharged particles attach themselves to the ions by virtue of electrostatic attraction, and so increase the mass of the ions. It has been calculated from diffusion measurements that ordinary gas ions (small ions, or molecular ions) generally consist of a cluster of about thirty molecules. The charge is independent of the number of associated particles; it may remain a single elementary charge, but further charged ions may attach themselves. Apart from electrons, positive atomic ions, and positive or negative molecular ions, 'large ions' (sometimes called 'slow ions') also exist. These deserve mention because they are sometimes present at the commencement of ionization measurements, when they hinder the attainment of the saturation current.

In contrast to the case of electrolytic ions, we must accordingly assume for gas ions an important difference between positive and negative ions; the positive ones are always associated with a mass of atomic order of magnitude, but the negative ions sometimes occur as electrons, particularly when the pressure of the gas is low.

This has an important bearing in connexion with the ionization of gases by collision. We have already seen that for an ionized gas the form of the curve relating the current and the applied potential is represented by Fig. 2, the current remaining constant (saturation current) after a certain value of the potential has been reached. But the value of the current does not remain constant indefinitely as we increase the potential between the electrodes, and at normal pressure a sudden spark ultimately passes between them. If the same experiment be performed with the gas at a reduced pressure of a few centimetres of mercury, we are readily able to determine the exact form of the current-potential curve for the gas, up to the potential at which a luminous discharge takes place. At first it is as in Fig. 2; but when a certain critical potential has been reached, the current again begins to increase, slowly at first, then with increasing rapidity until a glow discharge is initiated. The value of the critical potential depends on the pressure, being less for lower pressures. This renewed increase of the current after the critical potential has been reached is due to the fact that the ions between collisions acquire sufficient energy in the strong electric field to produce further ions by their collision with the neutral molecules of the gas. As mentioned above, when the pressure of the gas is low a considerable fraction of the negative ions exists in the form of electrons, and it is these ions which at first give rise to the growth of the current after the critical potential has been attained; later, however, the positive ions also participate in the process. In this way it is possible to maintain a current of about one thousand times the value of the saturation current. This kind of ionization of a gas, in which the ions initially produced gain sufficient energy by their acceleration in the electric field to produce fresh ions by collision, is called 'ionization by collision'. We shall meet with a very important application of this phenomenon in connexion with the counting of α- and β-particles by means of the point counter and the tube counter (see p. 17).

5. Methods of Measurement for the Rays from Radium

Every well-defined effect of the rays from radium can of course be utilized, in principle, for the purpose of their quantitative comparison. Thus it is very simply shown that radium preparations do not change appreciably in the course of a year, by comparing with each other the blackenings they produce in a given time on a photographic plate (cf. Fundamental Experiment 1), but very exact results cannot be obtained in this manner. Moreover, in quantitative work we should hardly have recourse to the heating effects of radium (Fundamental Experiment 6), since they can be measured accurately only with fairly strong preparations. The best and most general method has been found to be the action of the rays on gases, the insulating power of which for electrical charges is reduced by the rays from radium (Fundamental Experiment 3). As we have seen in the previous section, this phenomenon is based on the ionization of the gases, and can be utilized in a simple manner as the basis of a method of measurement.

Let us suppose that we have a positively charged hemispherical shell of copper, the edge of which rests on a slab of a good insulator, e.g. paraffin wax, and which is surrounded by air. The charge on the hemisphere flows to earth as soon as we touch it with a wire, the other end of which is connected to earth. Normally, air is not capable of conducting electricity, but if we bring a radium preparation near to the charged hemisphere, the air becomes conducting, and electricity now flows through the air in much the same way as if we had brought the hemisphere in contact with an earthed conductor. The air is rendered conducting by the rays from radium, and the degree of conductivity is greater the stronger the radium preparation with which we are working.

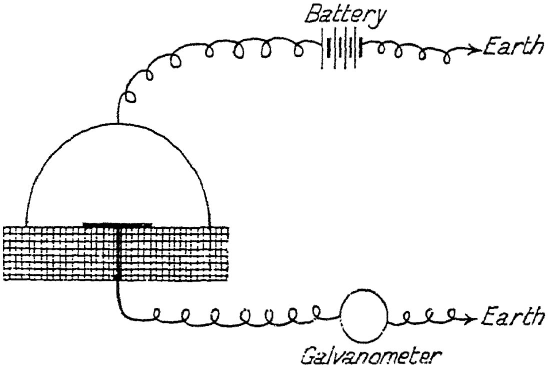

Fig. 3. Apparatus for Measuring Strong Radioactive Preparations.

A slight adaptation of the apparatus just described will serve as an exact measuring instrument. In order to measure the conductivity imparted by the rays from radium to a definite and well-defined quantity of air, we can use that inside the charged hemisphere. As nearly as possible in the middle of the sphere is situated a circular metal plate which rests on the paraffin slab. Connected to this plate is a wire that passes through the slab and is attached to one terminal of a galvanometer, the other terminal of which is earthed, as seen in Fig. 3. The preparation to be measured is laid on the metal plate, the hemisphere is placed over it, and this is connected to a source of potential of from 1,000 to 2,000 volts. If the preparation is not radioactive, the air within the hemisphere will remain an insulator, so that electricity cannot flow between it and the metal plate, and the galvanometer remains undeflected. But if in consequence of the rays emitted by the radium preparation the air between the hemisphere and the plate is ionized, an amount of electricity corresponding to the strength of the ionization will pass from the hemisphere to the plate and through the galvanometer to earth. Thus the current registered by the galvanometer is a direct measure of the ionization produced in the enclosed air, and hence also of the strength of the radium preparation (as shown in section 4), provided the applied potential is sufficiently high to ensure that the maximum or saturation current in the ionized air is attained.

The galvanometric measurements described above can only be carried out with very strong preparations, because the saturation currents obtainable in air are always very weak (see p. 10, footnote), and hence we are obliged to use other more sensitive apparatus, such as is not otherwise used in the measurement of current. For this purpose the electroscope occupies the foremost position. In its simplest form this instrument consists of two strips of metal foil attached at their upper ends; on charging them, the strips diverge. The amount of this divergence is greater the more highly they are charged, and in electroscopes that have been adapted as measuring instruments the divergence of the leaves can be read off on a scale placed behind them. Under normal conditions the leaves remain deflected for a long time, and only gradually collapse ('natural leak'), for the air has very pronounced insulating properties. But if we bring a radium preparation into the neighbourhood of the electroscope, the leaves collapse more or less quickly in accordance with the degree of conductivity imparted to the air by the preparation. If one preparation is twice as strong as another, it imparts to the air twice the conductivity, and hence the leaves collapse at twice the rate, provided that the experimental conditions are maintained exactly the same in the two cases. Thus the time required by the leaves to pass over a given number of divisions of the scale is inversely proportional to the strength of the preparation. Here also the magnitude of the saturation current serves as a measure of the ionizing action. If the volt-calibration of the scale of the electroscope, and the capacity (C) of the entire measuring system, measured in cm., are known, we can calculate the saturation current in the following way: Suppose the leaves collapse from V_1 to V_2 in t seconds, then the drop in potential is (V_1-V_2), and the quantity of electricity that has leaked away is $C(V_1-V_2)$. The electric current, or the quantity of electricity that has passed in one second, is consequently $C(V_1-V_2)/t$. Since 1 volt $= \frac{1}{300}$ electrostatic unit, we must divide the above result by 300 in order to obtain the saturation current in electrostatic units. Our final expression for the current is thus

$$i\text{ (e.s.u.)} = C\frac{V_1-V_2}{300t}\ (V_1 \text{ and } V_2 \text{ expressed in volts}).$$

The exceeding simplicity of its use, its rapid action, and its small cost make the electroscope the most favoured instrument in radioactive work.

According to the purpose for which they are primarily required, we differentiate between different types of electroscopes. Fig. 4 shows an

'α-ray electroscope', i.e. an electroscope which, although it permits of the measurement of all three types of rays, has in general too small a sensitiveness for the relatively smaller action of the β- and γ-rays. In this electroscope we have an ionization chamber *AB* into which the preparation is introduced, and it is separated by an amber or sulphur insulating plug *S* from the chamber in which the electroscope leaf *L* is situated. Passing through the plug *S* and connected with the plate *A* is a thin metal rod *C*, which is charged to a definite potential when the instrument is in use, whereas the plate *B* is directly connected to the earthed outer metal vessel.

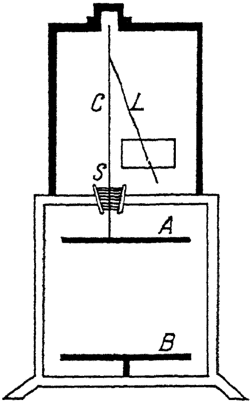

FIG. 4. α-Ray Electroscope.

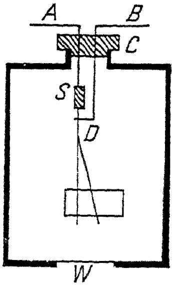

FIG. 5. β-Ray Electroscope.

In 'β-ray electroscopes' (see Fig. 5) the ionization chamber and the measuring chamber are combined, in order to diminish the capacity and hence to increase the sensitiveness. In the base of the instrument there is an opening which is closed only by a thin aluminium foil *W*; this prevents the α-rays from passing into the instrument, but does not deter the β-rays. The walls of the vessel are of sufficient thickness to prevent the entrance of β-rays. The active preparation is centrally placed beneath the aluminium window. As γ-rays are often present also, they are measured with the β-rays in such a β-ray electroscope, but their effect can generally be disregarded as compared with that of the β-rays. The same electroscope can also be used as a 'γ-ray electroscope' if we close the window *W* by means of a metal plate of the same thickness as the walls of the electroscope, instead of by aluminium foil. The electroscope is charged through the bent wire *B*, which rotates n the insulating ebonite stopper *C*, and can thus be brought into contact either with the earthed case of the instrument or with the leaf-support *D* below the insulating plug *S*.

If we require to make measurements with gaseous radioactive substances, we make use of a so-called 'emanation electroscope'. In thi instrument the ionization chamber is a closed airtight vessel. Fig. 6 illustrates one of the many possible forms of th instrument, and is sufficiently clear to need no furthe explanation.

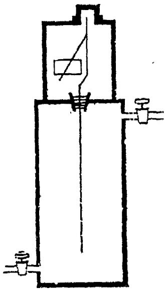
FIG. 6. Emanation Electroscope.

Thin Wollaston wire or fibres of platinized quartz have been found very satisfactory in place of the metallic leaves of electroscopes, especially when w are concerned with precisional measurements. In the 'single-string' (fibre) electrometer the insulated fibr is fixed at both ends and situated between two meta plates connected to the poles of a battery of from 50 to 100 volts, the mid-point of which is earthed When the fibre receives an electric charge, it is attracted by the oppositely charged plate; the amount of the deflexion gives a indication of the potential acquired by the fibre, and during a measurement the motion of the fibre is observed by means of a microscop with an eye-piece scale. In the 'double-string' electrometer the tw adjacent insulated fibres are attached at both ends and repel each other when charged, so that the subsidiary voltage plates are unnecessar The potential acquired by the system is indicated by the separatio of the fibres when charged, and, as before, readings are taken with microscope with an eye-piece scale.

When working with the rays from a radioactive substance it is i many cases preferable to measure the rate of charging of a previous uncharged electroscope or electrometer, instead of observing the discharge rate with the instrument initially charged. The principle involved in all these methods is the same, however; we are always concerned with the measurement of the saturation current produced in a ga

In general such instruments are used to establish the presence radioactive substances, and in these circumstances comparative measurements adequately fulfil our purpose. But if we desire to carry o absolute measurements, we must be able to determine the absolu value of the saturation current, and from what has already been sai it will be clear that we must then know the capacity of the instrume and the voltage calibration of the scale of the electroscope. We sha refrain from discussing the methods of measurement in greater deta here, as they are to be found in the special works referred to in th Preface.†

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† For convenience, several different units have been introduced for the measurem of radioactive substances (1 curie, 1 mache, 1 eve, etc.). These different units are de with in Chap. XXIII, under the headings of radium and radon.

Finally, special mention should be made of those measuring instruments that enable us to investigate the effects of individual α- and β-particles. The simplest means of recognizing individual α-particles is to make use of a substance which has the property of becoming luminous under the action of the rays from radium (cf. Fundamental Experiment 2, p. 1). Most suitable for this purpose is zinc sulphide which has been prepared in a particular way (see p. 243); this substance is so sensitive towards α-rays that each incident α-particle gives rise to an independent flash of light, which can be seen with the aid of a lens. From the number of these 'scintillations' which appear over a measured area of a screen coated with zinc sulphide, we can calculate the total number of α-particles that have been emitted by the radioactive preparation during the time of observation.

This method was of inestimable value especially in the study of the phenomenon of atomic disruption, since it was found that not only the α-particles, but also the H-particles arising from atomic disruption, call forth scintillations when they are incident on zinc sulphide screens. But it is difficult to exclude the subjective element (visual fatigue) in such observations, and for this reason electrical counting methods are often to be preferred, as they can readily be equipped with an arrangement for the automatic registration of the particles. They possess also the further advantage (sometimes a disadvantage) that they respond not only to α- and H-particles but also to β-particles and even to γ-ray impulses. There exist a variety of forms in which these electrical counting methods have been developed. We shall only discuss he two that are most important at the present time, viz. the point-ounter and the tube-counter, both of which were introduced by Geiger.

The general arrangement of the apparatus used with the point-ounter can be seen in Fig. 7.

The rays pass through a very thin mica window into a chamber, in the middle of which is situated an insulated metal point or needle. This point is connected to earth through a high resistance, whilst the walls of the chamber are connected to a source of positive high potential. Each time an ionizing particle enters the chamber through the mica indow and passes the neighbourhood of the point, a point discharge akes place by virtue of ionization by collision (see p. 11). This prouces a sudden deflexion of the fibre of a sensitive string electrometer tuated between the point and earth. By suitable choice of the values the applied potential, the gas pressure and the resistance, the sensiveness of the instrument can be varied within wide limits, and it can so be made applicable to the registration of individual γ-ray impulses.

When we are concerned with the measurement of a very small flux radiation, as with the cosmic radiation or the investigation of the artificial radio-elements, the sensitivity of the point-counter is often inadequate. In such cases the tube-counter can be used, since it is very much more sensitive. The tube-counter consists essentially of a metal tube, along the axis of which is stretched a thin wire whose surface is coated with a badly conducting film of uniform thickness. In consequence of the insulating action of this film, the potential between

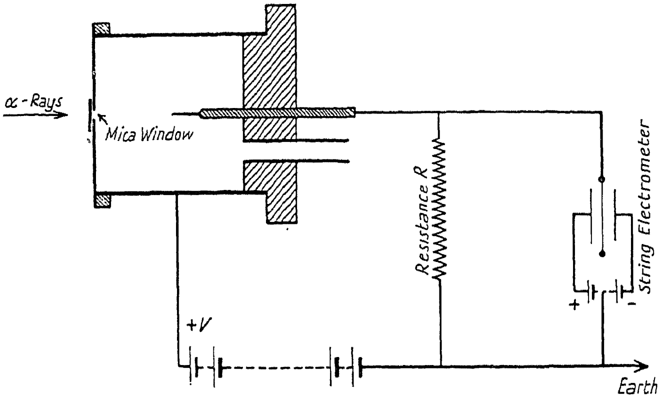

Fig. 7. Geiger's Point-Counter.

the wire and the tube can be raised beyond the normal spark potential under the prevailing conditions. If at any position inside the tube a small number of ions is produced, the resulting ionization by collision causes an appreciable quantity of electricity to flow to the wire, and this momentary current can be detected with an electrometer, just as in the case of the point-counter described above. Nevertheless, the exceedingly high sensitivity of the tube-counter makes it less suitable than the point-counter for the study of certain problems; for instance this applies when we wish to detect a weak α-radiation alongside a relatively intense β- and γ-radiation.

A third method which enables us to investigate the action of individual rays is the 'cloud method'. This is based on the fact that supersaturated water vapour condenses preferably on ions. Thus, if by means of a suitable arrangement we produce a supersaturated condition of water vapour in a gas space, in which an ionic track has been produced by a particle of radioactive origin, then in the absence of dust this water vapour will only condense where there are ions, and the track of the particle will consequently become visible as a line of fog. The apparatus used for this purpose was devised by C. T. R. Wilson, and in its earliest and simplest form it is represented diagrammatically in Fig. 8. The movable piston *b* is suddenly lowered by opening the main valve whereby a connexion is established between the vacuum chamber and that part of the apparatus situated beneath the piston. This causes an expansion in the space a, as a result of which water-vapour supersaturation occurs in the gas content of this space, which is maintained moist by artificial means. If rays enter the expansion chamber in a horizontal direction from a radioactive substance mounted in a side

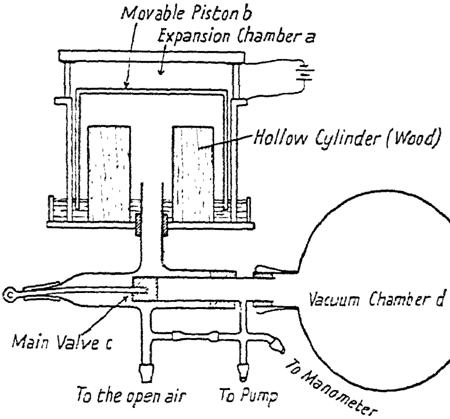

FIG. 8. Wilson's Cloud Chamber.

be of the chamber, these produce ions which are of course at first visible. However, those ions which are formed during or immediately fore or after the expansion serve as condensation nuclei for the water pour that is in a state of supersaturation at that moment. Tracks nsisting of a close array of very tiny droplets are produced in this y, and since the apparatus is closed at the top by a sheet of plate ss, these rows of droplets are visible with suitable illumination as ite fog tracks on a dark background. They can also be photographed, d by use of two cameras stereoscopic photographs can be obtained, means of which the path of the particle in space can be accurately estigated. This method has proved invaluable not only for counting particles, but also for the study of the fate of the individual particles ring their flight. With the aid of this method sudden changes in the ection of the tracks have been detected, and these have led to important conclusions about the collisions occurring between the particles gas molecules (see Fig. 14, Plate I).

he recording of individual α-ray tracks in the emulsion of a photophic plate is described on p. 32.

REFERENCE

MAKOWER and H. GEIGER, *Practical Measurements in Radioactivity* (Longmans, Green & Co., London, 1912).

II

THE α-RAYS

1. Mass and Charge of the α-Rays

As already mentioned, it follows from the direction of the deflexion experienced by α-rays in a magnetic field that they consist of positively charged particles. They are also deflected in an electric field. If we combine the magnitudes of the electric and magnetic deflexions, we obtain a quantity which is always very characteristic of charged particles, viz. the ratio of the charge to the mass of the particle, or the specific charge, e/m. We shall consider as the unit of charge the elementary charge of electricity, i.e. that of a mono-valent ion ($e = 4{\cdot}8 \times 10^{-10}$ e.s.u.), and as the unit of mass the mass of a hydrogen atom

$$m = 1{\cdot}67 \times 10^{-24} \text{ gm.}$$

In terms of these units we obtain for e/m in the case of α-particles the value $\frac{1}{2}$, i.e. such a particle either carries a single elementary charge and has an atomic weight = 2, or it carries two elementary charges and possesses an atomic weight = 4. We are able to decide between these alternatives both by physical and by chemical methods.

A luminescent screen, e.g. a surface coated with zinc sulphide, is caused to emit a flash of light by the incidence of every single α-particle upon it. If we count these scintillations, and determine in addition how much positive electricity is conveyed to an electrometer from the same source of α-rays under identical conditions, we obtain the amount of charge carried by a single particle by dividing the second number by the first. The result is found to be two elementary units of charge. From this it follows that the mass of the particle has the value 4, the atomic weight of helium.

This result is confirmed by the following chemical experiment. If we introduce radon or some other α-rayer into a glass tube with thin walls (< 1/100 mm. thick) and seal it off, it is found that the α-particles pass through the tube. But if this tube be now enclosed in a wider evacuated tube with sealed-off ends and thick walls, we are no longer able to detect α-particles outside the latter. The particles must therefore have been retained in the space between the glass tubes or in the walls of the outer one. As a matter of fact, it has been found possible to detect the appearance of helium in the intermediate evacuated space by means of the spectroscope (cf. Fundamental Experiment 5 on p. 1 The amount of helium produced by 1 gm. of radium in one year has the value 172 mm.[3]

We are thus led to the conclusion that α-particles are helium atoms with which are associated two positive elementary charges.

If α-rays are produced during a radioactive transformation, then the process proceeds in such a manner that each disintegrating atom gives ise to one, and only one, α-particle. This important fact was established y means of counting experiments, in which the number of the atoms isintegrating in a given time was known, and the number of α-particles mitted in the same time was determined by the optical method already eferred to, or by an electrical method. One of the best electrical methods s based on the fact that a momentary point discharge always occurs rom a highly charged needle point when a passing α-particle ionizes he air in the immediate proximity of the point. The method of using his point-counter has already been described on p. 17.

The number of α-particles emitted per second by 1 gm. of radium, ee from its products of disintegration, has the value $3{\cdot}7\times10^{10}$, and hen the radium is in equilibrium with three of its disintegration roducts that emit α-rays, the number is four times as large. From is we can calculate how many helium atoms must be contained in e 172 mm.^{3} of helium that are produced from 1 gm. of radium to-ther with its disintegration products as far as RaD in the course of year. This number of helium atoms is clearly

$$3{\cdot}7\times10^{10}\times4\times365\times86{,}400 = 4{\cdot}66\times10^{18}.$$

ccording to the value of Loschmidt's number obtained by quite different ethods, there must be present in 1 c.c. of every gas at N.T.P. $2{\cdot}7\times10^{19}$ olecules, so that theoretically we should expect 172 mm.^{3} of helium to ntain $2{\cdot}7\times10^{19}\times0{\cdot}172 = 4{\cdot}65\times10^{18}$ atoms. This excellent agree-ent offers convincing proof of the correctness of the atomistic concep-n of matter, for in the example just given it has been possible literally count the number of atoms which occupy a definite volume of a gas.

Absorption Range and Velocity of the α-Rays

we bring a preparation which emits α-rays, e.g. a surface coated with lonium, near a zinc-sulphide screen, the latter is found to become ninescent under the action of the rays. On gradually removing the paration, the luminescence of the screen suddenly ceases at a distance the radioactive film from the screen which in this case amounts to 7 cm. (at 15° C.). The ionizing† and all other actions of the rays disappear at the same distance (cf. however, the remarks on p. 28).

If we introduce the radioactive film into an α-ray electroscope, the two plates of ionization chamber being separated by considerably more than 3·87 cm., we still that the preparation produces an effect on the electroscope. Diffusion and transport e ions of the air in the electric field result in their gaining admittance to the whole e intervening space before recombination occurs, and hence the electroscope loses harge.

The existence of a sharply defined limit beyond which no further ionization takes place is a most characteristic property of the α-rays. The determination of this 'range' can be performed with great accuracy by a variety of methods.

In Table 1 are collected together the various radio-elements that emit α-rays, together with the ranges and initial velocities of their

TABLE 1

Ranges and Initial Velocities of α-Rays at 15° C. and Atmospheric Pressure

Substance	*Range in cm.*	*Velocity in cm./sec.*
Uranium I [1]	2·63	$1{\cdot}39\times10^9$
Uranium II [1]	3·18	1·48
Ionium	3·19	1·48
Radium	3·39	1·51
Radon (Ra Emanation)	4·12	1·61
Radium A	4·72	1·69
Radium C	4·1	1·61
Radium C′	6·96	$1{\cdot}92_2$
Radium F (Polonium)	3·87	$1{\cdot}59_3$
Thorium	2·59	1·38
Radiothorium	4·02	1·60
Thorium X	4·35	1·64
Thoron (Th Emanation)	5·06	1·73
Thorium A	5·68	1·80
Thorium C	4·78	1·70
Thorium C′	8·62	$2{\cdot}05_2$
Protoactinium	3·67	1·55
Radioactinium	4·68	1·68
Actinium X	4·37	1·65
Actinon (Ac Emanation)	5·79	1·81
Actinium A	6·58	1·89
Actinium C	5·51	1·78
Actinium C′	6·57	1·89

α-particles. From the last of these we can calculate the energy of th particles, the resulting value for RaC′ being $7{\cdot}68\times10^6$ electron-volts which is the energy that an electron would acquire in a vacuum if i fell through a potential difference of $7{\cdot}68\times10^6$ volts. We see that th α-particles from thorium have the shortest, and those from thorium C the longest range. The ranges given in the table are the 'practica or extrapolated ranges, the significance of which is shown in Fig. 11 the ranges of the individual particles fluctuate about a mean rang which is roughly 1 per cent. shorter than the extrapolated range.

In Fig. 9 (Plate I) are shown the tracks of a very large number α-particles of normal range from thorium C′; in addition, the track of

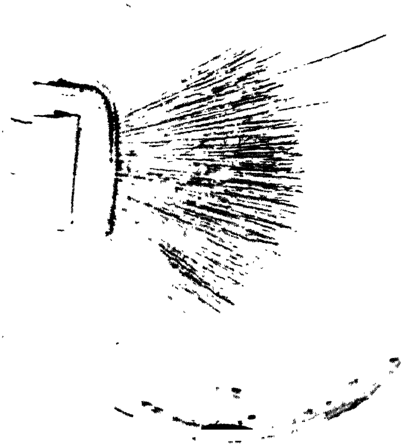

FIG. 9 (p. 22). Tracks of α-Particles from Thorium C′.

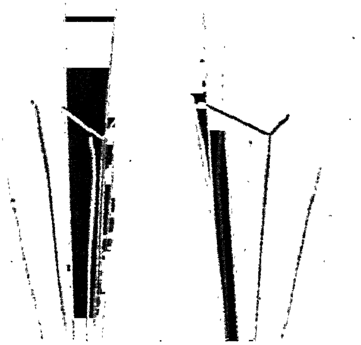

FIG. 14 (p. 32). Deflexion of α-Rays by Oxygen Nuclei.

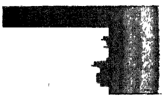

FIG. 17 (p. 40). Magnetic β-Spectrum of the Members of the Actinium Series (RdAc, AcX, AcB, and AcC).

ticle of the extreme long range (11·6 cm.) can be seen, as well as t of a particle of 9·8 cm. range (see p. 27).

The range is inversely proportional to the pressure of the gas, and ectly proportional to the absolute temperature. Hence α-rays exhibit y large ranges in a high vacuum.

o a first approximation the range is proportional [2] to the cube the velocity of the α-rays. The velocity, and hence the range of articles, can be influenced by the application of strong longitudinal tric fields. Thus the effect of a potential difference of 10,000 volts to modify the range of the α-particles from polonium in air by 6 mm.

wing to the much greater densities of liquids and solids, the range -particles in them is much smaller than in gases. The α-rays from anium preparation are absorbed by a sheet of aluminium of thick- 0·018 mm., and the much faster rays from ThC′ by a sheet of kness 0·065 mm. Accurate range determinations in liquids and in ls are much more difficult to carry out than in gases, but even with reliable values have been obtained by special methods. For ple, Table 2 contains the values found for the ranges of the

TABLE 2

Range of the α-Particles from RaC′ in different Metals [3]

Metal	*Range* (μ)	*Metal*	*Range* (μ)	*Metal*	*Range* (μ)
Li	141	Si	47·2	Ag	19·8
Be	42·8	K	150	Sn	30·1
C	35·1	Fe	19·4	Pt	13·1
Mg	59·5	Cu	18·2	Pb	25·6
		Mica	36·0		

ticles from RaC′ in several solid elements. We see that the range ishes as the density of the material increases. In water, the range rays from RaC′ has the value 60·0 μ, and 50·0 μ in the sensitive f a photographic plate.

the purpose of practical measurements a medium can also be niently characterized by the statement of its 'air equivalent', d of by the range. This term refers to the thickness of a layer which would reduce the range of an α-particle by just the same t as the medium in question. Mica, for example (density = 2·87), form of a thin sheet of such thickness that it weighs 1·50 mg. per ., has an air equivalent of 1·0 cm. (at 760 mm. and 15° C.). If trapolate for thicknesses which would correspond to the whole in air, the above determined air equivalent does not always e correct range of the α-rays in the substance concerned. This is due to the fact that air equivalents themselves are dependent on th velocity of the rays, and hence one and the same sheet, introduced a different points of the trajectory, shortens the range in air by differen amounts.

In the investigation of the behaviour of different media with respec to the same α-rays we often take account of the 'stopping power' instead of the range or the air equivalent. The stopping power of a medium is the quantity that expresses how many atoms of a standar substance are equivalent to an atom of that medium as regards absorption. Air is usually chosen as the standard substance. What has bee said of the air equivalent holds here also, but the idea of stoppin power becomes unequivocal as soon as we speak of the *average* stoppin power, e.g. when we understand by the stopping power of aluminiu for the α-rays from RaC′ that quantity which expresses how man 'atoms' of air an aluminium atom is able to replace *on an averag* throughout the whole of their path. As will be mentioned in greate detail later, the retardation of the α-rays in their passage near to o through an atom is due to the fact that the α-particle transmits energ to the atom, in which process the electrons in the atom take up orbi of higher energy content, or may be entirely removed from the ato (ionization). The stopping power must accordingly be determine primarily by the number of electrons in the atom, and secondari by their arrangement. The dependence of the stopping power (s) on th atomic number (Z) is clearly shown in Fig. 10. It is connected with th atomic number by the relation $s = 0{\cdot}563\dfrac{Z}{\sqrt{(Z+10)}}$.

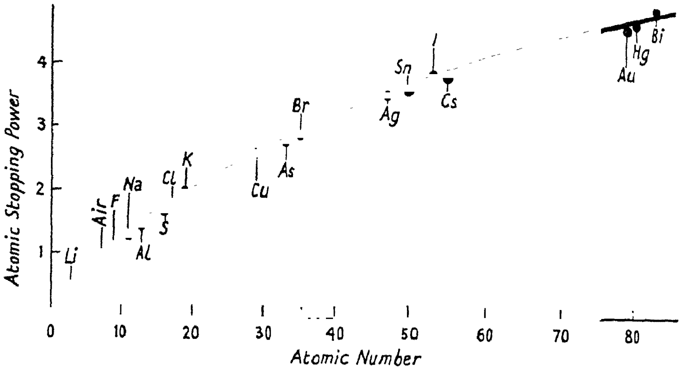

FIG. 10. Dependence of Atomic Stopping Power on Atomic Number.

The stopping power of a molecule is derived additively from those its constituent atoms, but this relation is not strictly valid. Conside able deviations from the additive law are found only in the case of the ightest of the elements; thus from the stopping power of the H_2-mole- ule we obtain for the H-atom the value $s = 0{\cdot}200$, whereas the com- ounds C_2H_4, C_2H_6, CH_4, when we make use of the value for C found vith diamond, yield the value 0·187, and from NH_3 we obtain the value ·173. The stopping power of water vapour is smaller by 3 per cent. han that of an equivalent mixture of hydrogen and oxygen [4]. For O_2 and CO the additive law was found to have strict validity. As pplied to α-rays of different range, the stopping power of atoms shows nly approximate constancy. It increases with increasing range when ıe atomic weight of the absorbing substance is greater than the mean tomic weight of air (14·4), and it diminishes with increasing range in ıe converse case. The absorption of a compounded sheet, consisting layers of two different materials, is for this reason dependent on hich side of the sheet faces the source of radiation. An exact calcula- on of the stopping power in terms of universal constants is possible those cases, for which the velocity of the incident α-rays is much eater than the velocity of revolution of the electrons in the atom that e responsible for the effect. Thus it is found that calculation is in cord with experiment in the case of the lithium atom, the stopping wer of which is twice that of an atom of hydrogen.

In their passage through matter, α-rays suffer a very considerable ninution in velocity, in consequence of which the phenomenon scribed above arises, viz. that the α-rays soon lose their characteristic perties (excitation of fluorescence, blackening of a photographic te, ability to ionize), and so reach the end of their range. If we regard the very last part of the track of an α-particle, a simple ıtion is found to exist between the velocity and the range of the ticles. At any point of the track the distance remaining to be versed is proportional to the cube of the velocity at that point p. 23). Thus from this relation we can calculate the initial velocity he α-rays from RaA, which we find to be $1{\cdot}69 \times 10^9$ cm./sec; from eriments on the magnetic and electric deflexion of the rays the e value is derived. For purposes of comparison it may be mentioned positive rays with a velocity of $2{\cdot}7 \times 10^8$ cm./sec. are able to ionize ugh a distance in air of about 1 mm. The velocities of the α-rays from various radio-elements are tabulated in the third column of Table 1 2). The decrease in velocity of the α-particles from RaC′ caused by traversing sheets of various thickness of aluminium, mica, and air own in Table 3.

a rule, α-rays cannot readily be detected after their velocity has reduced below about 0·4 of its initial value. Under particularly urable conditions, especially in high vacua, it is possible to detect

TABLE 3

Decrease in Velocity of α-Particles from RaC′ after passing through various Materials

Relative velocity v/v_0	Mass in gm. per sq. cm.		
	Aluminium	*Mica*	*Air*
0·95	$1{\cdot}48\times10^{-3}$	$1{\cdot}43\times10^{-3}$	$1{\cdot}24\times10^{-3}$
0·90	2·79	2·75	2·32
0·80	5·01	4·86	4·08
0·70	7·03	6·40	5·46
0·60	8·50	7·50	6·48
0·50	9·64	8·47	7·29
0·415	10·46	9·35	7·96

α-rays down to 0·23 of their initial velocity (cf. p. 31, and Table p. 33). It has also been possible to measure the diminution in veloci and in energy of an α-particle by determining the heating effect the α-rays after they have passed through a layer of gas of variab thickness.

Accurate investigations have shown that for certain radio-elemen the whole of the α-particles do not leave the atom with the same velocit By means of deflexion experiments in very strong magnetic fiel (23,000 oersteds) a fine structure of the α-particles from thorium (range = 4·8 cm.) has been detected. The relative velocities an intensities of the individual components of this fine structure can seen from the following Table 4 (cf. Table 24, p. 99).

TABLE 4

Fine Structure of the α-Particles from ThC

Group	*Relative velocity*	*Relative intensity*
α_2	1·0000	100
α_1	1·0034	30
α_3	0·9758	3
α_5	0·9624	2
α_4	0·9640	0·5

The difference in range between the first and second lines on amounts to about 0·5 mm. in air, that between the second and t relatively weak third line 3·5 mm., and that between the fourth a fifth lines 5·2 mm. Furthermore, both actinium C and actinon em α-particles of different velocity. On the other hand, the α-rays emitt by the remainder of the radio-elements are homogeneous; this h been established for the rays from polonium with an accuracy of per cent.

n the case of ThC′ and also RaC′, however, it is found that a small tion of the α-particles have a much longer range than is stated in le 1. Corresponding to each million α-rays emitted by ThC′ there 65 and 180 respectively with ranges of 9·8 and 11·6 cm (see p. 23 and 9), and in the case of RaC′ there are at least nine different groups -particles of long range, as indicated in the accompanying Table 5.

TABLE 5

Velocity Spectrum of the α-Rays from RaC′

Velocity (in cm./sec.)	*Energy (in electron volts)*	*Relative numbers of α-particles*
(Cf. Table 1)		
$1{\cdot}922 \times 10^9$	$7{\cdot}68 \times 10^6$	10^6
1·998 ,,	8·30 ,,	0·49
2·093 ,,	9·12 ,,	16·7
2·127 ,,	9·41 ,,	0·53
2·146 ,,	9·58 ,,	0·93
2·175 ,,	9·84 ,,	0·60
2·191 ,,	9·99 ,,	0·56
2·215 ,,	10·21 ,,	1·26
2·242 ,,	10·47 ,,	0·67
2·259 ,,	10·62 ,,	0·21
		Total = c. 22 ($\div 10^6$)

latter case these ranges are distributed over an interval up to a of 11·3 cm., and there are about 22 particles of abnormally long to each million α-particles emitted by RaC′. On p. 100 will be a discussion of the connexion between these α-particles of ab- lly long range and the γ-rays that are emitted simultaneously. range of H-rays (see p. 67) accelerated in the forward direction α-rays from ThC′ is equal to 40 cm. It may be mentioned connexion that the range of H-rays is just as large as that of of the same velocity. Moreover, the stopping power is the same h.

e Ionization produced by α-Rays

sequence of its large velocity, an α-particle possesses at the ing of its path a very considerable kinetic energy amounting to 10^{-5} ergs, or roughly 10^{11} times the value of the thermal energy lium atom at room temperature. By virtue of this kinetic energy les give rise to strong ionization along their tracks by their ns with gas molecules. Thus an α-particle from RaC′ produces s track of length 6·60 cm., in air at atmospheric pressure and $\cdot 20 \times 10^5$ pairs of ions, i.e. equal numbers of positive and of negative ions. The total number k of pairs of ions produced by a arbitrary α-particle amounts approximately to

$$k = k_0 R^{\frac{2}{3}},$$

where k_0 is a constant $= 6{\cdot}3 \times 10^4$, and R signifies the range at 0° C.

The intensity of ionization of the α-particles emitted by RaC′ in air in its dependence on the distance from the source of the rays, is repre sented in Fig. 11. It is seen that quite near to the end of the track th

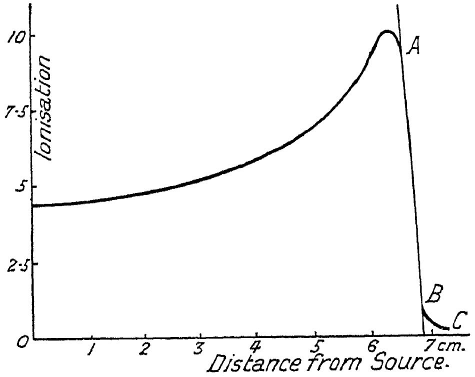

FIG. 11. Variation of the Ionization produced by an α-Particle with Increase of Distance from the Source.

ionization increases considerably, and then diminishes very

The last part BC of the graph shows a feeble tailing off, probably d to scattering. In consequence of this the range cannot be obtained fr the graph with precision, so that it is customary to produce the rec linear part AB of the graph until it cuts the abscissa, and to consider t distance of this point of intersection from the origin as the 'practical' val of the range. In the above case the maximum value of the ionizati occurs 3 mm. from the end of the track of the particle. Fig. 12 illustrat the alteration which takes place in the ionizing power of α-particles they pass through air, compared with the corresponding changes e perienced by the number and by the velocity of the particles. The curves are representative of the case of the α-rays from RaC′ at 15°

If several α-rayers are simultaneously present in the source, the cur of ionization has a more complicated form. Fig. 13 shows the ionizati curve of the active deposit of thorium. The occurrence of such a cur always indicates the presence of a heterogeneous radiation, or sin each α-transformation is accompanied by a homogeneous radiation bears witness of the presence of different products emitting α-ray Just as an analysis of the curves representing the variation of activ with time (see Chap. XI) renders possible the interpretation of t ess of disintegration, so we can also make use of an analysis of the e of ionization for the same purpose. Thus Fig. 13 shows that there wo α-rayers in the active deposit of thorium, namely ThC and ThC′, ranges of 4·8 and 8·6 cm. respectively.

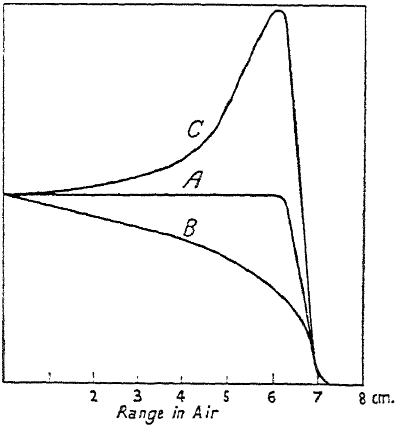

FIG. 12. Absorption of α-Rays in Air. *A*: Number of Particles; *B*: Velocity; *C*: Ionization.

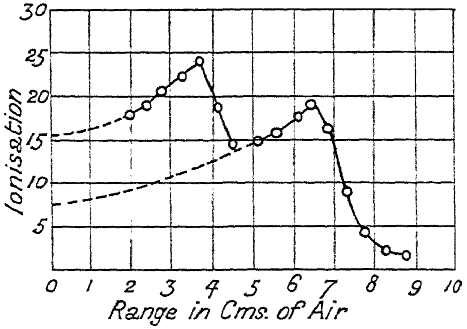

FIG. 13. Curve of Ionization due to Presence of two α-Rayers (ThC and ThC′).

n a parent substance is in equilibrium with several disintegration ts, the part played by the individual disintegration products ling up the total ionization depends not only on the number, o on the ranges of the individual α-rays. Thus the ratio of the on produced by ThX+Thoron+ThA+ThC to that produced h is 4·59, the relative ionizations due to these five substances espectively 1·61, 1·78, 1·92, 1·71, and 1·53.

the energy necessary to produce a pair of ions depends on the f the gas, there exist between the values of the total ionization produced by an α-particle in various gases differences of varyi magnitude, according to the velocity of the α-rays used. Thus for α-ray from polonium of residual range 7 mm. we find the following relati values for the total ionization (Table 6). The amount of energy expende

TABLE 6

Relative Ionization of the α-Rays from Polonium in different Gases

Air	1
Helium	1·26
Neon	1·28
Argon	1·38
Nitrogen	0·98
Oxygen	1·08

by an α-particle in the production of a pair of ions is almost independe of the velocity of the α-particle. In diatomic gases the ionization is les than in monatomic gases. Most of the ions produced possess a singl electronic charge. In hydrogen, oxygen, chlorine, mercury, etc., there about one doubly charged ion to every 600 singly charged ions, wherea in helium about 16 per cent. doubly charged ions have been observe

In Table 7 are shown the amounts of energy, expressed in electro

TABLE 7

Ionization Potentials of different Gases

Gas	*Energy necessary in electron-volts*	*Ionization potential in volts*
Hydrogen	32·5	15·8
Helium	27·6	24·5
Nitrogen	35·6	15·8
Oxygen	32·2	12·5
Argon	25·2	15·7

volts, which are necessary to produce a pair of ions in certain gase together with the ionization potentials of these gases. The number pairs of ions produced by an H-particle per cm. of its path is onl one-quarter of that produced by an α-particle of the same velocit

As already mentioned on p. 20, the counting of scintillations, addition to ionization measurements, plays a very important part the detection of α-particles. The scintillation method is extraordinari useful especially when we require to detect α-particles in the presence a strong β- or γ-radiation. Zinc sulphide screens (see p. 243) are able transform up to 25 per cent. of the kinetic energy of α-particles in visible light energy. For a practised eye about 30 quanta of green lig ($\lambda = 0{\cdot}5\,\mu$) suffice for the unaided visual perception of a scintillation

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[†] When a microscope is used for counting, the energy entering the eye must be ab 300 quanta, or about 1200 quanta for reliable counting.

g the α-rays from RaC′, the smallest velocity which is just able to rise to scintillations amounts to 13 per cent. of the initial velocity e rays. β-rays excite strong fluorescence in zinc sulphide, but they ot produce scintillations. If, however, several β-rays strike the tiny zinc sulphide crystal simultaneously, sufficient luminous gy may be emitted to produce a visible scintillation.

cattering of α-Rays

allow the α-particles from a point source to pass in a narrow pencil gh thin metal foils, e.g. through a gold sheet of thickness 1/100 mm., hen to fall on a scintillation screen held in different angular posi- with respect to the initial direction of the pencil, we find that ction of the α-rays is deflected through a small angle from their al direction. This scattering is explained in the following way. -particle is deviated through a minute angle in every individual through which it passes, in consequence of the electrical forces iling there; and when the α-particle passes successively through e number of atoms in the gold foil, these atomic deviations are imposed to form a larger and measurable deviation.

'scattering coefficient' ϕ, i.e. the most probable angle of deflex- r a sheet of such thickness that its air-equivalent is 1 cm., is dent on the material of the foil, and for the α-rays from RaC′ it e following values:

	Au	Ag	Cu	Al
$\phi =$	2·1°	1·5°	1·1°	0·6°

e experiment has shown that the deflexion caused by an atom hly proportional to the weight of the atom, it follows that the menon of scattering is detectable mainly in the passage of the hrough heavy atoms. ϕ increases, moreover, as the velocity of article diminishes, and is inversely proportional to the second or ower of the velocity. The deviation also increases proportionately e square root of the thickness of the scattering material, and the olds for its dependence on the number of atoms per c.c. of the ing material.

ell as this 'multiple scattering' there is another very important f scattering, namely 'single scattering', which arises from the tion between α-particles and atomic nuclei (see p. 95). In the nentioned observation of scattering by the scintillation method ound that a few particles are scattered through relatively large and quite a small number that have been deflected through 90° re can be seen on the luminescent screen. Thus it was found that aC′ was used as source, one particle in 8,000 was deflected through more than 90° in the passage of the rays through thin platinum foil. These large deviations are the result of 'single scattering', for the can only originate from a single collision. The probability is vanishingl small that the α-particle in its passage through a thin metal sheet wil come twice or more often so effectively close to an atomic nucleus.

If the scattering of α-rays by light atoms is observed in an intermediate angular range, multiple and single scattering may be equall important. We then speak of 'plural' scattering. The relative magnitude of multiple scattering as compared with single scattering depend on the thickness of the scattering sheet.

The scattering of α-particles can also be established by photographi means. For this purpose the source of the rays is laid on the photographic film, and after development the tracks of the particles are seen as a series of radial lines of blackened points (i.e. silver bromide particles that have been struck by α-particles), and some of these show sudden bends, sometimes through large angles. A special photographi emulsion has recently been prepared, and this facilitates the detectio of the presence of a very weak α-radiation by exposure of the plate t the radiation for some months [5]. The range of the particles can b determined in this [illegible]. In experiments with the cloud method th phenomenon of scattering is very clearly revealed. Fig. 14 (Plate I shows not only single deflexions but also the effect of a violent collisio between an α-particle and an oxygen nucleus. Here the α-particle wa deflected from its original path through 76° 6′, and the direction o the recoil track of the oxygen atom struck makes an angle of 45° 1 with the initial direction of the α-particle. The photograph was obtaine by taking two exposures simultaneously on the same film, so as t get the track of the rays from two directions mutually perpendicula Scattering played an important part in the investigation of the constitution of atoms, and we shall discuss it further in that connexion. At thi juncture it will suffice to mention that, from the ratio of the number o α-particles that are deflected through an angle ϕ from the origina direction of the rays to the number falling on an equal area in the sam time when no scattering sheet intervenes, it is possible to calculat the nuclear charge of the scattering element. The mean value of vario observations in the case of platinum was 77·4, whereas the corre value is 78 (see p. 86); the corresponding figures for silver are 46 and 47, and for copper 29·3 and 29.

5. Capture and Loss of Electrons by α-Rays

If α-particles pass through a narrow slit and strike a photograph plate, and we observe the deviation of the beam of rays under th action of a magnetic field, we obtain in general one line corres deviation of He^{++}. At the highest vacua, however, a second line aled, which has suffered a deviation only half as large as that main line, and which is produced by singly charged α-rays The smaller the velocity of the α-rays, the more distinct is the ne as compared with the He^{++} line. For the very smallest veloci- re is also an undeviated line, due to neutral α-particles (He^0). s passage through absorbing atoms an α-particle can accordingly p an occasional electron, and on rare occasions it may even a second electron. But these electrons are soon cast off again, the course of the flight of an α-particle this capture and loss of ns is repeated several thousand times. Table 8 shows the ratio numbers of singly and doubly charged α-particles (He^+/He^{++}), s equal to the ratio of the mean free paths (λ^+/λ^{++}) of the particles.

TABLE 8

apture and Loss of Electrons by the α-Particles from RaC′
Initial Velocity $V_0 = 1{\cdot}922 \times 10^9$ *cm./sec.*

Velocity V/V_0	*Range in cm.*	He^+/He^{++} *or* λ^+/λ^{++}
0·94	5·79	0·005
0·76	3·06	0·015
0·47	0·72	0·133
0·32	0·23	0·53
0·29	0·17	1·00
0·27	0·14	1·5
0·23	0·08	3·0

ease in the number of He^+-particles very near to the end of the also shown in the investigation of the deviability of the α-rays magnetic fields as high as 40,000 oersteds. In these experi- is found that the curvature of the track caused by the magnetic s not continuously increase with decreasing velocity of the that it passes through a maximum value very near the end ge. This result is explained by the fact that towards the end nge He^+- and He^0-particles occur, and in consequence the ue of the charge of the α-particles diminishes. Since a diminu- arge acts on the deviability of the rays in the contrary sense minution in velocity, the possibility arises of the occurrence of m curvature for a particular velocity.

ect of the change in the charge of the α-particles is also notice- e occurrence of fluctuations in the range of the particles. At ent of their emission the α-rays from a single radioactive all possess the same velocity (cf., however, p. 26). As soon ave traversed a sheet of an absorbing substance, however, sufficient to reduce appreciably their velocity, the pencil of rays begi to be inhomogeneous. If we determine the range by scintillation coun we find that the limit at which the scintillations disappear is n sharp, but that the number of scintillations gradually falls off with a region of from 3 to 4 mm. As measured by means of a point counte the mean breadth of this region of straggling has been found to b 2·95 mm. for the α-particles from ThC′ in air at 15° C. and 760 mm pressure. The breadth of straggling of from 3 to 4 mm. is but litt dependent on the nature of the absorbing material, and is approxi mately just as large for α-rays of long as for those of short range. Th fluctuations in range of the α-particles, at the end of their path, a related fundamentally to the fact that both the transfer of energ during individual collisions and the fluctuations in density of the g molecules have a statistical distribution.

6. Probability Fluctuations in the Emission of α-Rays

If we count the number of scintillations produced on a scintillati screen by a constant and homogeneous source of radiation in interva

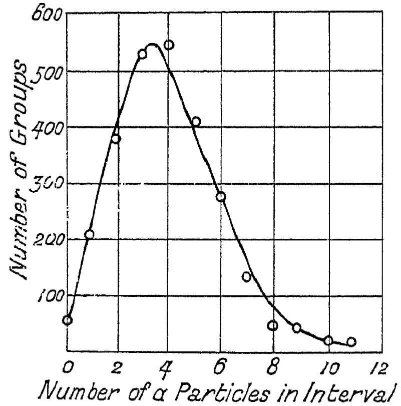

FIG. 15. Fluctuations in the Rate of Emission of α-Particles.

of, say, 15 sec. duration, we find that the values fluctuate; in some cas they are larger, in others smaller than the average value. By t average value we mean the number which results when the number scintillations counted in, say, 2 hours is divided by 480, i.e. the numb of 15-second intervals in 2 hours. The smaller the intervals duri which counts are made, the greater are the fluctuations obtained. Th phenomenon is a particularly simple example of probability fluctu tions, the presence of which is always demanded by the statisti interpretation of natural phenomena, when the magnitudes we obser are only average values.

abscissae of Fig. 15 show the numbers of α-particles counted in ond intervals, whereas the ordinates represent the number of ments of that duration in which these numbers of particles were ed. The results are in accord with those found from the calculus babilities.†

n the emission of α-particles, we can also detect a probability tion in the measurements of their ranges.

represents the mean value, then the probability p that n particles will be emitted n interval of time is given by

$$p = \frac{a^n}{n!}e^{-a}.$$

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III

THE β-RAYS

1. Mass and Charge of the β-Rays

The deflexions experienced by β-rays when they pass between th poles of a magnet or between the plates of a charged condenser sho a great similarity in direction and in magnitude to those found wi cathode rays. It has been shown by deflexion experiments in a magnetic field that, just as the cathode rays possess different velociti according to the manner of their production,† so also we find rays different velocity in the investigation of the β-rays from radioacti substances. Here, moreover, we meet with velocities‡ of magnitu much greater than are ever reached by cathode rays; thus with Ra there are β-rays with a velocity 0·998 of the velocity of light. In acco dance with the theory of relativity the mass of a body is dependent its velocity of translation. In practice this dependence does not becom manifest until the velocity is very considerable, i.e. of the order magnitude of the velocity of light.‖ Thus, in the case of β-rays of lar velocity, we are led to expect a marked dependence of the mass of β-particle on its velocity, and this has been established, in comple accord with the demands of the theory of relativity. Correspondingl we differentiate between the 'rest mass' and the 'translational mas of β-particles, i.e. the mass of the particle in motion. For the former t

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† When they leave the cathode the electrons already have a mean thermal ener of $1{\cdot}725\times10^{-4}\,T$ electron-volts.

‡ Apart from the velocity of an electron (v) measured in cm./sec., use is frequen made of the ratio (v/c) of the electronic velocity to the velocity of light as a meas of the velocity. In calculations, especially for small velocities, we frequently ha recourse to the velocity expressed in volts (V), i.e. that difference of potential in vo through which an electron originally at rest would have to fall *in vacuo* in order to atta the velocity v:

$$V = 511{,}000\left\{\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}-1\right\}.$$

A further measure of the velocity which is often used when the velocity is the magnetic-deflexion method is the product of the magnetic field strength (H) a the radius of curvature (r):

$$Hr = 1{,}702\frac{v/c}{\sqrt{(1-v^2/c^2)}}.$$

‖ The mass m corresponding to the velocity v is given by

$$_0\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}},$$

where m_0 = the rest mass, c = the velocity of light. Whereas particles with a veloc 1/10 that of light only show an increase in mass $\frac{1}{2}$ per cent. greater than that of the p ticles at rest, the value of m for particles with 0·998 of the velocity of light is 15·8 ti the value of m_0.

value was found as for the rest mass of a cathode-ray particle, $\cdot 105 \times 10^{-28}$ gm., which corresponds to 1/1,837 of the mass of m of hydrogen. Thus we conclude that β-rays consist of rapidly g electrons.

en β-rays fall on a positively charged electrometer they discharge versely, a preparation emitting β-rays becomes positively charged it is insulated *in vacuo*, as can be shown by connecting it to an meter. Using radium preparations, and exercising great care as insulation, it is possible in this manner to attain a charge correng to a potential of +150,000 volts (see also the 'radium clock',). It is possible to determine the number of β-particles emitted nown quantity of radium, by noting the charge acquired by an meter to which it is connected, in consequence of the escape of cles. Another method of counting β-particles is based on the use point counter (p. 17), which is also used with advantage for the ng of α-particles, as mentioned on p. 21.

ne case of α-transformations we saw that one atom emits only article, and it is likewise found that in the transformation of a such as RaB or RaC each disintegrating atom emits only one le. From the combined amounts of RaB and RaC in equilibrium gm. of radium $(2 \times 3{\cdot}7) \times 10^{10}$ β-particles are emitted in each (cf. p. 21). The simplicity of the conditions prevailing in such ents is very much masked by the occurrence of secondary rays, shall discuss this when we are dealing with secondary rays.

orption and Velocity of β-Rays

onding to their large velocity, the penetrating power of most s considerably greater than that of α-rays. In their passage matter, the intensity of the rays gradually diminishes, and the s of the layer by which they are 'completely' absorbed depends nall degree on the delicacy of the absorption measurements, ion to the hardness of the rays.

the investigation of the β-radiation from RaE, for instance, as abscissa the thickness of the absorbing sheet of aluminium, rdinate the ionization produced by the radiation, we obtain regular graph. The values of the ordinates diminish in geoprogression as the abscissae increase in arithmetical progreshe intensity of the radiation is reduced to half its value in its hrough a layer of thickness 0·16 mm. Al, after passing through mm. it is reduced to a quarter, and so on. Accordingly, the e thickness' of aluminium for the β-rays from RaE has the

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crease in the radioactivity of every simple disintegrating radioactive substance according to the same type of curve (see graph B in Fig. 41, p. 128).

value 0·16 mm. The steeper the downward slope of the above-me tioned absorption curve, the more easily are the rays absorbed, and t smaller is the value of the half-value thickness. Instead of the las named quantity we often consider the 'absorption coefficient', usua designated by μ,[†] and equal to $\frac{0·693}{\text{half-value thickness}}$.

The absorption curves do not always show the simple form j described, which can be represented mathematically by means o single absorption coefficient; for their interpretation it is often necessa to assume the existence of a mixture of rays, i.e. different absorpti coefficients. Thus the β-rays from RaB exhibit the absorption coe cients 13, 77, and 890 when they are passed through aluminium. T absorption coefficients of different β-rays in aluminium are given Table 9.

TABLE 9

Absorption Coefficients of different β-Rays

Radio-element	*Absorption coefficient μ in aluminium*
UX_1	460
UX_2	18
Ra	312
RaB	13, 77, 890
RaC+RaC″	13, 50
RaD	5,500
RaE	43

When the absorption coefficient is small, the half-value thicknes large, i.e. the penetrating power is large; for this reason such rays a also called 'hard', in contradistinction to the easily absorbed 'soft' ray

If we investigate the absorption of one and the same β-radiati in different materials, we find that the absorption coefficient increa with the density of the absorber, but that the ratio of the two quantit is not strictly constant. Table 10 contains a number of values of t ratio of the absorption coefficient to the density, or the mass-absorpti coefficient, for a variety of solid elements, and for the β-rays from U whereas Table 11 gives a comparison of the absorption coefficients β-rays of different hardness in air and in carbon dioxide.

The absorbing power of a chemical compound is built up additiv

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[†] If I_0 is the intensity before absorption, and I the intensity after the rays h passed through a layer of thickness d, then $I = I_0 e^{-\mu d}$, where μ = the absorption coe cient. Putting $I = \frac{I_0}{2}$, we find $\mu = \frac{\log_e 2}{d_{\frac{1}{2}}} = \frac{0·693}{d_{\frac{1}{2}}}$ cm.$^{-1}$ Thus the 'half-value thickne is related to the 'absorption coefficient' in the same way as the 'half-value period' the 'disintegration constant'. (Cf. p. 127.)

TABLE 10

atio of the Absorption Coefficient to the Density of the Absorber

Substance	*Density*	*Absorption coefficient* *density*
Carbon . . .	1·8	4·4
Sulphur . .	2·0	6·6
Boron . . .	2·4	4·65
Aluminium . .	2·7	5·26
Barium. . .	3·8	8·8
Iodine . . .	4·9	10·8
Tin . . .	7·3	9·46
Copper . . .	8·9	6·8
Lead . . .	11·3	10·8
Gold . . .	19·3	9·5

TABLE 11

bsorption Coefficients of different β-Rays in Air and in Carbon ioxide (at 1 atmos. and 22° C.), arranged in decreasing order hardness of the β-Rays

Radio-element	*Air*	*Carbon dioxide*
$ThC+ThC''$.	0·0068	0·0129
RaE . .	0·0152	0·0297
ThB . .	0·090	0·142
UX_1+UX_2 .	0·12	0·23
RaD . .	0·64	1·69

ose of its elementary constituents, but in the case of hydrogen nds there exist deviations from this rule.

ge of the β-Rays. β-Ray Spectra

t be expected that in the matter of absorption β-rays would similar behaviour to α-rays. It is found, however, that β-rays by the various radio-elements are absorbed in their passage matter according to the same laws as are rays of light (cf. This behaviour is accounted for by the fact that the β-rays by a radio-element do not possess a definite velocity like the but show a continuous velocity spectrum, which is discussed 4. With the aid of a magnetic field the continuous spectrum analysed into its component velocities, and in this way the of the individual components can be evaluated. The energy ion in the continuous β-ray spectrum of a few radio-elements en from Fig. 16 (cf. also the discussion on p. 105). The analysis in a magnetic field yields the further result that a line spectrum ies is found to be superimposed upon the continuous spectrum.

It may be mentioned in advance that the continuous spectrum β-rays originates in atomic nuclei, whereas the line spectrum is p duced in the electronic shells of the atoms. These questions are d cussed in greater detail on p. 101. Each line in the magnetic spectrum of β-rays (cf. Fig. 17, Plate I) corresponds to a homogene radiation, i.e. to rays of definite velocity. When we investigate the sorption of such a β-radiation in aluminium we obtain graphs that almost straight lines, at least in the earlier stages of absorption. Fig

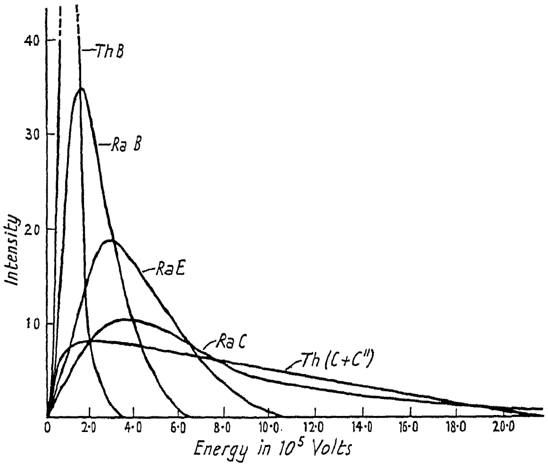

FIG. 16. Energy Distribution in the Continuous β-Ray Spectrum of Various Radio-elements.

shows the absorption of β-rays having a velocity of 0·83 that of li In order to obtain a magnitude analogous to the range of α-rays may produce the line *AB*. The distance from the origin to *D* t represents the 'practical' range of the β-rays, i.e. the thickness of layer of aluminium sufficient to absorb practically all the β-rays. approximate rectilinear form of this graph is the result of two su imposed processes, the process of scattering and the diminution of velocity of the rays. (For details, see p. 47.) On replacing the alumini by paper, which has a smaller scattering power, the graph assum somewhat concave form, whereas lead, which has a larger scatte power, gives a convex form to the graph, relative to the origin.

Fig. 19 shows the 'practical' range of β-rays of different veloci aluminium. Along the abscissa axis are plotted the velocities fractions of the velocity of light—and the ordinates represent the ra measured in gm. of aluminium per sq. cm.† The product of the ra

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† In the case of aluminium with a specific gravity of 2·7, 1 gm. per sq. cm. corresp to a thickness (range) of 3·7 mm.

PLATE II

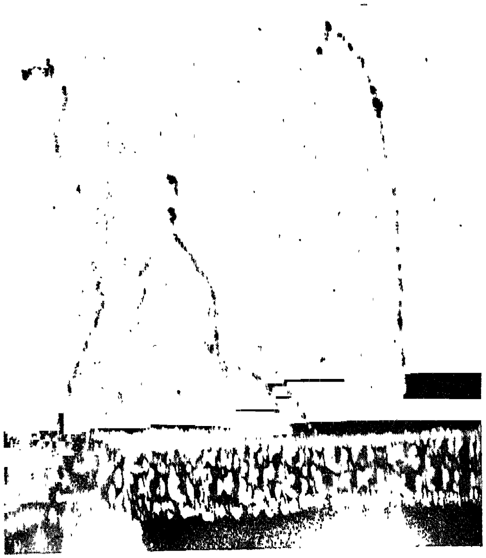

FIG. 20 (p. 41). Tracks of β-Rays from RaD in Air at 20 cm. Pressure.

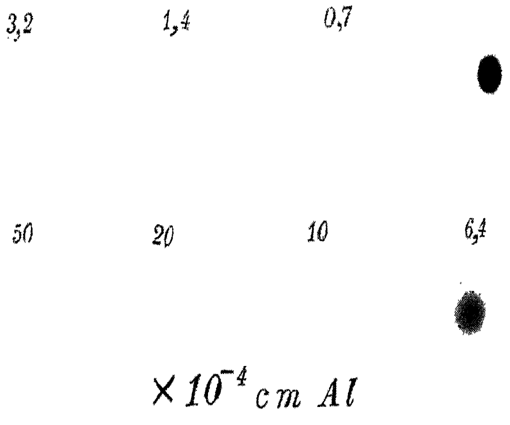

FIG. 21 (p. 45). Scattering of β-Rays after passing through Aluminium Foil.

he density of the absorbing material is practically independent material. The stopping power of an atom is roughly proportional e atomic number, but more accurate investigation reveals a licity of the stopping power. The presence of a well-defined range β-rays can also be shown by cloud photographs. Thus the β-rays RaD comprise two strong β-ray groups having velocities corre-ing to 34 and 39 per cent. of the velocity of light, and having es corresponding to 31,000 and 43,000 volts respectively. The cloud

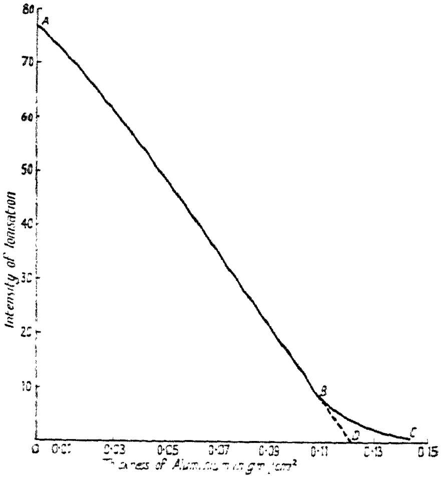

FIG. 18. Absorption of Homogeneous β-Rays in Aluminium. ($v/c = 0{\cdot}831$).

ıph (Fig. 20, Plate II) shows two mean ranges of 0·8 and 1·58 cm. al pressure and room temperature. We are here dealing with ınges, or the real lengths of path traversed by the electrons hey are completely stopped. The curves that represent the nce of the logarithm of the ionization current on the thickness ial traversed, or the logarithmic absorption curves for β-rays, rally straight lines. Because of this fact it was at one time d that we were here concerned with homogeneous rays. That ıt true follows from what has been said above, and also from :hat if, instead of deriving the absorption curve by measuring ation current with the aid of an electroscope, we make use r counter (see p. 37), the resulting curve is no longer strictly ial in form. In the interpretation of this result, however, we e into consideration that the counter indicates a smaller ıf the scattered electrons than the ionization method, and reater efficiency of the slower particles in producing ionization ·ctive in the case of the counter.

The investigation of magnetic spectra resulted in the detection of large manifold of lines, of which, in the spectrum of RaC for examp the existence of 63 has been established. (See also p. 101.) The fast β-rays (0·998 of the velocity of light) were detected in the magnet spectrum of RaC, whereas in the spectrum of ThC indications are fou of the existence, along with other lines, of β-rays of velocity only 0·

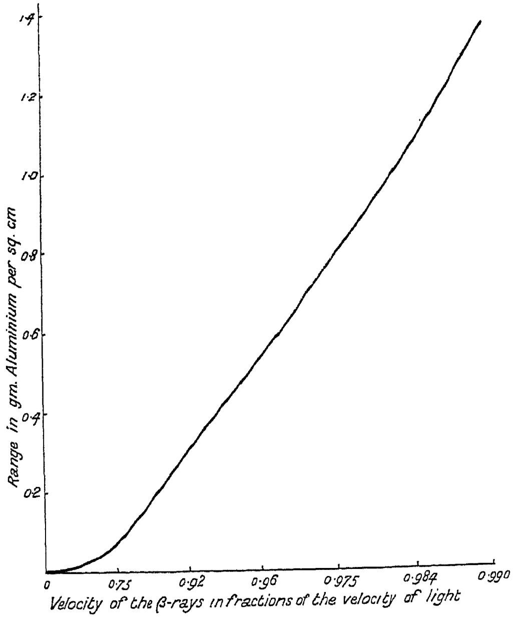

FIG. 19. Range of various β-Rays in Aluminium.

of the velocity of light. In their passage through matter β-partic suffer a considerable diminution in velocity, this amounting to 30 p cent. when rays of velocity 0·95 that of light pass through 2 mm. aluminium. In consequence of the diminution in velocity, the value the coefficient of absorption also alters during the passage of the r through matter. The thickness of the half-value layer is more th ten times smaller for rays of two-thirds the velocity of light than those which possess a velocity 95 per cent. of that of light. The dif ence of the squares of the energy before and after penetration of absorbing layer is roughly proportional to the thickness of the laye

The decrease in velocity experienced by β- and α-rays when th pass through matter is essentially connected with the characteris frequency of the electrons in the atoms, in a similar manner to t phenomena of refraction and dispersion.

he Ionization produced by β-Rays

ticles ionize the gas molecules lying in their track when their ity is not less than a certain minimum value, which in air amounts 0071 of the velocity of light; for in order to ionize, the particles have a certain minimum amount of energy. We can also consider advantage the energy instead of the initial velocity of the β-par-, and since the energy of an electrically charged particle is equal to oduct of its charge and potential (eV). and the charge of a β-particle ays constant and equal to the elementary electronic charge, we lso introduce the potential difference (V) in place of the energy ich it corresponds.[†] In these units the above-mentioned minimum ty corresponds to a potential difference of 13 volts. If we en- ur to ionize air by means of cathode rays, to which we impart the ary energy by accelerating them in a potential drop of sufficient tude, we find that a potential difference of 11 volts is necessary er to obtain ionization of the air. This quantity is known as the tion potential[‡] of air. That of hydrogen has the value 13·5 volts, at of helium 25 volts.

pite of their large velocity, the ionization produced in a given e by β-rays is much weaker than that effected by α-rays. A cle with a velocity of about 0·9 that of light produces in air at heric pressure 55 positive and an equal number of negative r cm. of its path, or only about $1/200$ the number produced by rticle. Since a β-particle collides with 8,400 atoms in each cm. ath in a gas at atmospheric pressure and normal temperature, led to the conclusion that only about 1 per cent. of the atoms are ionized. The large velocity of the β-rays influences very urably the yield in ions. As the velocity of the rays decreases, nber of ions produced increases considerably, but below a velo- ·024 that of light, at which velocity 7,700 ions are produced per begins to diminish. Corresponding to complete absorption, a le of energy represented by 300,000 to 350,000 volts produces out 10,000 pairs of ions; the mean value of the number of pairs produced per 1 cm. of path is about 70 at normal pressure. For f 39 per cent of the velocity of light (43,000 volts) it has been to establish by means of the cloud method the formation of ary ions per cm. of the path of the particle. If we take into

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hysical meaning of this difference of potential is that the β-particle would ired the same kinetic energy if it had traversed a difference of potential of itude, and without having an initial velocity. (Cf. the footnote on p. 36.)

nization potential can also be defined as the potential with which we have to he elementary charge in order to arrive at the work that must be performed an electron from its normal orbit within the atom to an infinite distance.

account that the secondary ionization amounts to about four times primary ionization, the total number of ions produced by such β-particle along the whole of its range in air can be calculated to about 1,000. The energy expended in the production of a pair of i corresponds to about 32 volts. Since the ionization potential of nitrogen molecule is only about 16 volts, we must conclude from t that a considerable part of the energy handed over by a quickly mov electron in its collision with molecules is utilized in performing w other than ionization, as in the excitation of molecules and simi processes.

For velocities not exceeding about 40 per cent. of the velocity light, the diminution in the velocity of electrons effected by sm thicknesses of matter is inversely proportional to the cube of velocity. In the case of platinum the constant of proportionality about four times as large as with aluminium. For very large veloci (85 to 95 per cent. of the velocity of light) the decrease in the ene of the electron is proportional to the thickness of the layer of mat traversed.

The number of ions produced per 1 cm. of path in one and the sa gas is proportional to the density of the gas, so long as the gas is att ated; for different gases the proportionality between the numbe ions produced and the density is only approximately valid. The ab numbers have reference to the total ionization caused by β-rays. general, the primary ionization amounts only to a fraction of the t ionization, and it arises by virtue of the fact that the primary β-parti ionize individual atoms. The number of these initially ionized ato can be evaluated by means of the cloud method, for a water drop is associated with each ion. The evaluation of the number of drop along the path of a β-particle of one-third the velocity of light yi for the number of primary pairs of ions produced about 90 per cm atmospheric pressure. This number is roughly inversely proportio to the square of the velocity of the particles.

5. Scattering of β-Rays

Whereas the scattering experienced by α-rays in their passage throu matter is detectable only by accurate observations, and is in pract without influence in absorption measurements, scattering is very imp tant in the case of β-rays, and it is not permissible to neglect it. T the ionization produced in an electroscope by β-rays that have pas through an absorbing layer of, say, aluminium foil is considerably grea when the foil is situated in the immediate vicinity of the electrosco than when it is immediately in front of the radioactive source, wh is usually placed at a distance of several centimetres from the elect

In both cases a fraction of the rays is scattered in traversing minium foil, but whereas in the former case almost the whole scattered radiation also enters the electroscope, in the latter it ot.

exceedingly intense scattering experienced by β-rays even when ss through quite thin sheets of aluminium is shown very clearly photographs reproduced in Fig. 21 (Plate II).

e photographs were obtained by allowing the β-rays emitted by nillicuries of radon to pass through a small circular opening, n to fall on a photographic film wrapped in black paper. When erimental vessel was evacuated during the exposure, the pencil was registered on the developed film as a sharply defined cir- tch of blackening. The introduction of a sheet of aluminium $0{\cdot}7 \times 10^{-4}$ cm. thickness in the path of the rays was sufficient, in the figure, to produce a distinct scattering of the rays, i.e. ution in sharpness of the edge of the area of blackening. For um foil of thickness 50×10^{-4} cm. the scattering was already so that the central spot is almost invisible. Of course the total of the rays remained practically unaltered, but in the latter was distributed over so large an area that the blackening posed on that resulting from the γ-rays vanished.

he purpose of determining the magnitude of the scattering by different substances, we first measure the ionization I l in a β-ray electroscope by a β-rayer situated on a supporting e thickness of which is as small as possible. The resulting n is produced exclusively by particles that enter the electro- ectly. If we now place a sheet of the substance under investiga- nediately beneath the radioactive source, some of the rays in the downward direction, which do not under normal cir- es reach the electroscope, are now deflected upwards by the onsequence of scattering, and the total resulting ionization I' ctroscope is greater than I. The 'percentage reflection' from is given by $100\,\frac{I'-I}{I}$; it increases considerably with the eight of the reflector, as can be seen from Table 12. The data rence to the β-rays emitted by RaE, and correspond to thick the reflectors.

mber of particles reflected increases with increasing thickness et, from which it follows that the reflection does not take place rface of the reflecting substance as in the case of light rays, h a way that the β-rays, in penetrating the atoms of the reflec- ften so strongly deflected from their path that this deflexion esemblance to reflection. The deviation of the β-rays is a consequence of the electrical forces existing within the atoms, and shall return to this subject on p. 79. The particles reflected in

TABLE 12

Reflection of the β-Rays from Ra E from different Substances

Substance	*Atomic weight*	*Percentage reflecti*
Bi	209·0	70·9
Pb	207·2	70·2
Au	197·2	67·8
Ag	107·9	57·4
Cu	63·6	44·7
S	32·1	32·1
Al	27·1	30·0
C	12·0	17·1

manner now pass through the atoms of the reflector in the rev direction, and so reach the electroscope. The increase in the num of the reflected particles ceases when the thickness of the reflec sheet is sufficient completely to absorb the reflected β-particles in t return journey through it.

For thin layers it is found that the mean angle of deflexio β-particles after passing through a layer of thickness x is proporti to the square root of x. For very small thicknesses the scattering is l than would be required by the square-root relation. If we comp the scattering in different elements for very small thicknesses, we f a greater scattering for elements of large atomic weight than wo result if it were proportional to the atomic number. The most prob angle of scattering is inversely proportional to the energy of the r but this relation has not yet been firmly established for high veloci

Every β-particle in its passage through atoms suffers as a rule alteration both in its direction and in its velocity, energy being gi up in the process to the atoms traversed. The diminution in velo is brought about mainly by the electrons of the atom, and the cha in direction by the influence of the nuclei. The electrons in the at are thus chiefly responsible for the absorption of the β-rays, and atomic nuclei for the scattering. As with α-rays (see p. 31), we differ tiate here also between 'single', 'multiple', and 'plural' scatteri With very thin sheets the larger deviations arise as a result of a si elementary process. There is then a very small probability tha particle will suffer more than one elementary deflexion of the orde magnitude under consideration; simple or single scattering resu The processes of simple scattering can be rendered visible by the cl method of investigation as sudden bends in the tracks of electr (Fig. 20, Plate II). The less probable the single deflexion we obser

reater the deflexions on which we focus our attention, the
ill be the thickness of the sheet up to which we encounter true
attering. The reverse holds for true compound or multiple
g. This can only be expected for small angles of scattering
thicknesses of the scattering material. The directional distri-
the scattered electrons can be approximately reproduced by
Gauss's law of errors. If the total deviation is composed in
f more than one single deflexion, but at the same time the
f single deflexions is not large enough for the strict application
s distribution law, we then speak of the process as one of
ttering.

radiation falls perpendicularly on a sheet of material we
inquire as to the amounts of it which leave the sheet respec-
the emergence and on the incidence sides. For α-rays the
that practically the whole of the radiation leaves the sheet
ergence side. With β-rays, on the other hand, an appreciable
f the β-particles is scattered in the backward direction; in
before the velocity has diminished considerably with increas-
ıess of the sheet, the number of electrons emitted on the
side already falls off because of this process of backward
There occurs what we might call a backward diffusion of
With the help of similar considerations to those indicated
e of α-rays (p. 32), we can calculate the magnitude of the
arge of the atoms responsible for the deviation, from the
of the individual deflexions of β-rays. The evaluation of
n of the particles deflected through more than 90° yielded
·1 for the nuclear charge of the oxyg[illegible] atom. The absorption
(see p. 37), or more correctly the 'coefficient of weakening',
lved into two components, the true coefficient of absorption
efficient of scattering. The 'atomic absorption coefficient',
uct of the true absorption coefficient and the atomic number
the density, is approximately constant within a period of
system of classification of the elements.

ison of the Absorption and Scattering of α- and β-Rays

e velocity of all the α-particles emitted by a unitary sub-
RaF diminishes uniformly in their passage through matter,
pencil of rays remains homogeneous and the number of
actically unchanged, the behaviour of β-rays is different.
and more particles are cut out by scattering during the
ı, and hence in the later parts of the path the ionization is
a small fraction of the particles emitted by the radiating
effect of this decrease in the number of the β-particles is

greater than that of the increase in the ionizing action resulting the reduction of velocity (see p. 43), and hence the ionization curve which the ionization is plotted as ordinate and the velocity of the as abscissa, show a downward trend from the beginning onward β-rays, in contrast to the curves for α-rays. Such a curve of ioniza for β-rays, and hence also the curve of absorption, is the result of var factors, such as the decreasing number of the ionizing particles, magnitude of the ionization produced by a β-particle which at increases as the velocity of the particle diminishes, and the additi ionizing action of the scattered β-particles. These last include those resulting from the action of the nuclear charges, and those have been scattered by the electron shells of the atoms traversed. they traverse matter, homogeneous β-rays thus become apprecia heterogeneous quite near the beginning of their path, and the expon tial form of the ionization and absorption curves of these rays is the resultant of the various contributory processes mentioned. We further take into account that, whereas the velocities of all α-rays are of the same order of magnitude and lie between 1·4 and $2 \cdot 1 \times 10^9$ cm./sec.,† the β-rays embrace a much bigger rang velocities. β-rays can be detected with energies of less than 100 and of more than 2×10^6 e.V. On the other hand, if we follow the tracks of 'single' β-particles, we obtain just as definite a rang with α-rays. For very slow electrons of velocity 25 e.V. or less the at of the rare gases are almost completely transparent; the mean path of such electrons is thus abnormally large (Ramsauer effect

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† The energies of α-particles with those limiting velocities are respectively 4·1 e.V. and $9 \cdot 2 \times 10^6$ e.V.

REFERENCE

A detailed description of the properties of β-rays will be found in *Radi* *from Radioactive Substances*, by RUTHERFORD, SIR E., CHADWICK, J., and E C. D. (Cambridge University Press, 1930).

IV

THE γ-RAYS

Nature of γ-Rays

l type of rays that we encounter in the investigation of radio-
ocesses is the γ-radiation. This is influenced neither by the
of electric nor magnetic fields, and it presents a radiation
ι nature to that of light, in contrast to α- and β-rays, which
particles projected rectilinearly from radioactive substances.
ıe spectral resolution of X-rays has been effected with the aid
rence phenomena in crystals, the application of the same
o γ-rays has also met with partial success.†
a cylindrical pencil of X- or γ-rays is incident on a crystal,
X- or γ-rays are emitted in different directions from the parts
stal involved, in a similar manner to the way in which rays
re diffracted from a diffraction grating. We can picture the
n of the diffracted X-rays most clearly by regarding it as a
of the original rays from the lattice planes in which the atoms
ed within the crystal. If only one such crystal plane were
the X-rays would be reflected independently of the 'colour'
ngth. There are, however, innumerable such lattice planes
rior of a crystal, always separated from each other by equal
d. The more or less penetrating X-rays manage to reach
ıese planes, and the radiation is reflected at all of them. These
ays suffer interference and annul each other, with the excep-
se rays for which the following simple relation exists between
-length λ, the glancing angle ϕ, i.e. the angle between the
ıy and the lattice plane, and the distance d separating two
ıes:

$$n\lambda = 2d\sin\phi.$$

ression n is an integer 1, 2, 3, etc., and indicates that reflec-
so take place for those angles the sines of which are double,
, that of the smallest effective angle. The intensity corre-
o these successive integers, however, becomes smaller and
st as in optics the spectra of the second, third, etc., orders
cessively weaker. In fact, the formation of X-ray spectra
bed is analogous to the resolution of light by means of a
he 'grating constant' is here the distance between two adja-
planes in the crystal, and it is of a much smaller order of

-length of the 'hard' γ-radiation is so small that even crystals are of no
liffraction gratings.

magnitude than in optics, owing to the much smaller wave-lengt the X-rays. For instance, in the case of a crystal of rock salt, d amo to only $2{\cdot}80 \times 10^{-8}$ cm., whereas the grating space of a Rowland gra is about 10^{-4} cm. If we rotate the crystal whilst a narrow pen 'continuous' X-radiation is incident upon it, say from an X-ray t we find that for each of several definite values of the angle ϕ a ho geneous X-ray 'colour' is reflected with particular intensity, and su posed on the uniform scattered radiation which shows up as a cont ous background in the spectrum. The presence of such an X-ray spe line can be recognized either by means of a photographic plate, w a sharp line appears, or by means of an electroscope, which experie a sudden increase in its discharge rate for each effective setting of crystal. A point-counter can also be effectively utilized for this purp

If ϕ and d are known, we can obtain directly from the formula value of the wave-length λ of the X-ray or γ-ray line in question. example, it is possible by the method described to establish the exist of 23 separate lines in the γ-spectrum of RaB + RaC, their wave-len lying between 5 and 3,000 X-units, where 1 X-unit $= 10^{-11}$ cm. the case of γ-rays of very short wave-length other methods are gene used instead of the method of crystal analysis, because the scatte then takes place within the individual atoms and not from the la planes. One other method that leads us more satisfactorily to objective is based on the calculation of the wave-length of the γ from the energy of the secondary β-rays produced by them (see p. A third method is based on the calculation of the wave-length of γ-rays from their absorption coefficient (see pp. 52 and 99).

Table 13 shows the approximate wave-length ranges for various t of radiation, including the γ-rays.

TABLE 13

Wave-lengths of the various Electromagnetic Waves

Type of rays	*Wave-length in cm.*
Electric waves .	From ∞ to 8×10^{-3}
Infra-red waves .	10^{-1} to 8×10^{-5}
Visible light waves .	8×10^{-5} to 4×10^{-5}
Ultra-violet waves .	4×10^{-5} to 10^{-7}
X-ray waves .	10^{-6} to 10^{-9}
γ-ray waves . .	10^{-8} to about 10^{-11}
Cosmic ray waves .	down to about 10^{-14}

2. Absorption of γ-Rays

The shorter the wave-length of the γ-rays, the greater is their pene ing power through matter, or the greater their 'hardness'. If we the thickness of the layer traversed as abscissa, and the intensi iation as ordinate, we again obtain to a first approximation an ntial curve,† as with the β-rays. But here the absorption co- : μ is usually much smaller, or the half-value thickness $\left(=\frac{0{\cdot}693}{\mu}\right)$ ı larger. Whereas the intensity of the most penetrating β-radia- ls to half its initial value after the rays have passed through . of aluminium, a sheet of lead of thickness 1·5 cm. is necessary :e the intensity of the hardest γ-rays to half its value.‡

increasing density of the absorbing substance the absorption nt generally increases, and the ratio between absorption co- and density is found to be approximately constant, even for ls like gases and heavy metals whose densities are so widely :. Hence for a gas the absorption is proportional to the density. ent of the deviations from this proportionality can be seen ble 14, in which are given for different substances the absorption

TABLE 14

on Coefficient in Different Substances of the γ-Rays from RaC

Substance	μ	$\frac{\mu}{\text{density}}$
Hg . . .	0·621	0·045
Pb . . .	0·533	0·047
Cu . . .	0·395	0·044
Fe . . .	0·356	0·045
Sn . . .	0·299	0·041
Zn . . .	0·322	0·045
Al . . .	0·126	0·047
S . . .	0·091	0·046
Water . .	0·055	0·055
Air at 15° C. .	$4{\cdot}64 \times 10^{-5}$	0·0378

t μ of the rays from RaC, and the mass absorption coefficient The softer γ-rays from RaC were eliminated by the introduc- filter of lead 4 cm. thick. The substances are arranged in the decreasing density. The number of electrons present in the f great importance in connexion with the ability of an atom to ıe intensity of γ-rays, but even if we calculate the weakening on, a dependence on the atomic number is still manifest. The n effect of a compound is obtained by adding together those ividual atoms present.

;ain we have $I = I_0 \epsilon^{-\mu x}$, where I_0 is the intensity before transmission through s x, and I is the intensity after transmission.

ance, in order to reduce the intensities of the α-, β-, and γ-rays from the active horium to half their values, we require 0·003, 0·2, and 15·0 cm. of paper

Between the coefficient of absorption μ and the wave-length λ th exists a relation which is quite well represented by the equation

$$\mu = A\lambda^{2.8}.$$

When we are dealing with homogeneous rays the wave-length ca directly calculated from the coefficient of absorption by means of equation. The value of the constant factor A depends on the natu the absorbing substance. This relation is no longer valid for very h γ-rays.

3. Scattering of γ-Radiation

In their passage through matter γ-rays are reduced in intensity i variety of ways: (*a*) they produce recoil electrons, as a result of wh the radiation suffers a diminution in frequency (Compton effect, se 57); (*b*) they lose energy by the production of positrons (p. 72; (*c*) t produce photo-electrons. A further complication of the condition absorption is caused by the fact that in the course of some of the ab mentioned processes γ-rays or recoil rays occur, and these are adde the radiation. Thus the positrons produced by the rays disappear production of a homogeneous γ-radiation (see p. 72), which is adde the original radiation. Moreover, the production of characteristi rays accompanies the liberation of photo-electrons, and these X will likewise manifest themselves in the weakened beam of radia When γ-radiation traverses very thick absorbing layers the occur of a very hard X-radiation is also observed, which was not origi present, and which arises from the production by the recoil elect (Compton electrons) of a very hard impulse radiation. For light elem the absorption takes place primarily by virtue of the Compton pro Thus for the γ-rays from ThC″ the reduction in intensity in alumi due to the production of positrons amounts to only 1 per cent. of brought about by the Compton process; in the case of iron the is 7 per cent., and for lead it is as high as 22 per cent. The absor resulting from the liberation of photo-electrons in lead amounts t per cent. of the Compton absorption in the same metal.

Whereas the Compton absorption per electron is independent o atomic number of the absorbing element, the calculated absor per electron due to the liberation of positrons is directly proporti to the atomic number, and the absorption due to the producti photo-electrons is roughly proportional to the fourth power of atomic number, except in the case of the heaviest elements for w the increase is less rapid [1]. The ratio of the frequency of occurren a Compton scattering process and a photo-electric process incr rapidly with increasing hardness or diminishing wave-length o

f the absorbing substance is uranium, then for rays of wave-
24·4 X.U. the above ratio is almost unity, whereas for the
γ-rays of wave-length 5·6 X.U. the frequency of a scattering
is twenty times greater than that of a photo-electric absorption
In light materials such as carbon the role of scattering is much
till, for here the above-mentioned ratio has the respective values
d 80,000. In such materials, for short-wave γ-rays like the
component of the radiation from RaC, true (photo-electric)
on fades into insignificance as compared with scattering. When
ely thin filter is used in conjunction with the rays, the absorp-
fficients are found to depend appreciably on the absorbing
this being ascribed to the absorption of the softer com-
of the radiation. The diminution of the full absorption co-
or the hardening of the γ-rays from radium after transmission
lead filters of increasing thickness is shown in Table 15.

TABLE 15

n of the Full Absorption Coefficient of the γ-Rays from Radium with the Thickness of the Lead Filter

cm. Pb	μ_{Al}	μ_{Pb}
0	0·176	..
0·5	0·153	..
1·0	0·144	0·715
2	0·137	0·615
2·5	0·135	..
3	0·129	0·540
4	0·126	0·533
7	..	0·533

thorough investigation shows that, in general, the γ-radiation
y the individual radio-elements is not homogeneous, but that
resolved into a few practically homogeneous components, i.e.
ponents that possess different full absorption coefficients.
shows the values of the full absorption coefficients established
nt radio-elements. Thus in the disintegration of RaB, which
med into the bismuth isotope RaC, we recognize the emission
ifferent types of radiation, the softest of which has an absorp-
icient of 230 and the hardest 0·57 cm.$^{-1}$ in aluminium. If
e rayed with hard X-rays, the bismuth reacts to this treat-
he emission of a kind of fluorescence radiation known as the
stic radiation of bismuth, which consists essentially of three
ys, the *K*-, *L*-, and *M*-radiations (see p. 63). The characteris-
on can also be excited by the bombardment of bismuth with

correspondingly energetic β-rays.† We are thus immediately confro with the question as to whether the three types of rays emitted by R are identical with the characteristic radiations of bismuth, produ in the atoms meanwhile transformed into RaC, during the escape and by the γ-rays originating in the RaB nuclei. The truth of t

TABLE 16

Full Absorption Coefficients (μ) of the γ-Rays

			μ in aluminium				
Radio-element	*N*	*Nature of Decay*	*M-radiation*	*L-radiation*	*K-radiation*	*Nuclear radia*	
UX_2	91	β	..	..	..	..	0·1
UX_1	90	β	..	24	0·7	..	..
$MsTh_2$	89	β	..	26	..	..	0·1
Io	90	α	1,088	22·7	0·41	..	..
RdAc	90	α	..	25	..	..	0·1
Ra	88	α	354	16·3	..	0·27	..
AcX	88	α	..	..	..	..	..
RaC	83	β	..	..	..	0·23	0·1
RaE	83	β	..	..	..	0·25	..
RaD	82	β	..	45	1·00	..	..
RaB	82	β	230	40	0·57	..	..
AcB	82	β	120	31	0·45	..	..
ThB	82	β	160	32	0·36	..	..
RaF	84	α	585	..	..	..	..
AcC″	83	β	..	..	..	..	0·1
ThC″	83	β	..	..	..	..	0·0

interpretation has been established, and accordingly the designati M-, L-, and K-radiations in Table 16 signify not the characteristic radiations of the disintegrating atoms but those of the resulting ato

In various other cases, however, one or two full absorption coeffici are also found, which are to be ascribed to very hard rays emitted the atomic nucleus itself; they cannot be interpreted as having ar in the atom during the escape of an α- or β-particle. In accordance w this, the last column of Table 16 is designated 'nuclear radiation'. shall return to this question in Chapter IX, after the discussion of problem of atomic structure. The already described diminution in value of μ with increasing filter thickness is due to the gradual cutt out of the softer rays. The truth of this is exemplified by the fact t in the case of the γ-radiation from ThC″, which is almost homogene even before being filtered, such a hardening effect does not take pl

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† The following relation exists between the velocity of the β-rays (electrons) expre in kilovolts (V) and the wave-length (λ) of the hardest γ-rays (X-rays) produced:

$$\lambda = \frac{12{,}340}{V},$$

where λ is expressed in X-units (10^{-11} cm.).

rption Measurements with γ-Rays as applied to Radio- Analysis

e presented with a mixture of radio-elements, the increasing n of the intensity of the radiation as the thickness of the absorb- rial increases shows a more complicated behaviour, and such nents can under certain circumstances serve for the qualitative of the presence of different radio-elements, just as in the he α-rays already discussed. This method can be applied to whether a preparation that must not be opened consists of ium or of radium, and if the former is the element present, even establish when the preparation was made. This result is possible by the fact that the penetrating γ-radiation from s derived exclusively from RaC (0·50 cm.$^{-1}$ in Pb), whereas esothorium preparation two hard types of γ-rays are emitted spective γ-rayers $MsTh_2$ (0·62 cm.$^{-1}$ in Pb) and ThC″ (0·462 b). Now whilst equilibrium is established between $MsTh_1$ and ly a few days after the preparation is made, the ThC″ radiation increases over several years, corresponding to the growth and hence the harder ThC″ radiation in mesothorium prepara- t be more strongly represented the older the preparation is. nce of a particularly hard radiation manifests itself by virtue t that, in comparison with a definite γ-radiation such as that lium preparation, thick plates of lead suppress the ionization in the case of a softer radiation. The measurement of the produced after filtration in 0·5 cm. lead is mostly used for rison of the intensities of the γ-radiations emitted by different ents [2].

TABLE 17

quivalent of Mesothorium and Radiothorium Preparations of Different Age

	Thickness of absorbing sheet of lead in cm.									
ration	*0·5*	*1·0*	*2·0*	*3·0*	*4·0*	*5·0*	*6·0*	*7·0*	*8·0*	*9·0*
prepared	1·00	1·02	0·96	0·88	0·79	0·71	0·64	0·60	0·57	0·55
s. old	1·35	1·38	1·38	1·35	1·32	1·29	1·27	1·27	1·29	1·32
s. old	0·90	0·93	0·97	1·00	1·02	1·04	1·07	1·11	1·15	1·20
	1·00	1·06	1·17	1·28	1·40	1·52	1·64	1·76	1·89	2·02

mpanying Table 17 illustrates the behaviour, as regards found with mesothorium preparations of different ages; ements were performed with a preparation of mesothorium about 20 per cent. radium.† The values are expressed in

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m content of mesothorium freshly prepared from Brazilian monazite is terms of the ionization produced by a radium preparation, used a standard. (In this connexion cf. also Fig. 48 on p. 233.)

From this table it is clear that when we have no knowledge of th conditions, the amount of mesothorium present as compared w radium is underestimated in the case of young preparations, especi when thick sheets of lead are used. As the age of the prepara increases, the amount of mesothorium is overestimated, and, at a la stage, again underestimated. Moreover, if radium be present in mesothorium, it can be detected qualitatively by the correspond alteration in time of the absorption. Nevertheless, the quantitat estimation of the different substances is fraught with great difficu mainly because in practice we nearly always have to deal with mixtu of mesothorium of unknown age with the element radium. Owing their practical importance, absorption measurements with radiothori have also been included in Table 17.

The age and the proportion of mesothorium in radium salts can be calculated, likewise without opening the preparation, from the r of the respective developments of heat by the radium prepara containing mesothorium and by a standard radium preparation. this connexion see p. 246 et seq.)

5. Ionization produced by γ-Rays

The γ-rays do not ionize directly, but split off electrons from molecules with which they collide, and these electrons, as β-ra ionize the gas molecules present. That no direct ionization takes p follows, in the first place, from the fact that the penetrating powe the secondary electrons liberated by the incidence of γ-radiation matter is independent of the length of the air-path previously traver by the γ-rays. Had the γ-rays given up energy by direct ioniza along this path, the energy of the secondary electrons would depend the length of the air-path already traversed by the γ-rays. In the sec place, we can deduce the absence of direct ionization from the appe ance of cloud photographs of a beam of γ-rays. The ionization tra shown by such photographs are always associated with the tracks β-particles.

The γ-rays emitted by the amount of RaC in equilibrium with 1 of radium produce a total of 11×10^{14} pairs of ions per sec. along th paths. This number is almost equal to the number of ions produced the β-rays from the same quantity of RaC; but since the lengths of tracks of γ-rays far exceed those of β-rays, it follows that the γ-r produce a correspondingly much smaller number of ions for each

responsible for 20 to 25 per cent. of the total γ-activity, and gradually increases in rela importance in consequence of the decay of the mesothorium.

path. Under normal conditions the half-value thickness of air se γ-rays amounts to 150 m., the corresponding thickness for eing 0·63 m. As mentioned on pp. 37 and 43, it has been estab- hat each disintegrating RaC atom emits one β-particle, and that duces 54 pairs of ions along 1 cm. of its path. We can also speak idual γ-impulses or 'photons', and calculate that a 'γ-particle', rrectly a photon, produces 1·5 pairs of ions per cm. of its path. corpuscular conception of γ-rays often simplifies the solution lems relating to γ-rays, and use is frequently made of it (see footnote). The number of γ-photons emitted per sec. by the of RaB+RaC in equilibrium with 1 gm. Ra is equal to ^{0} (cf. pp. 21 and 37), from which we may conclude that each ating atom emits approximately one γ-photon.

γ-rays eject β-particles from all substances, and not only from s of gases, the action of γ-radiation on an electroscope must on whether the absorbing medium, such as a lead plate, is near to the radiating preparation or to the electroscope, for rmer case the freed electrons or secondary β-rays from the reach the electroscope in much smaller quantity than in the n like manner the γ-rays liberate electrons from the whole rhood of the electroscope, from the walls of the room, from tc., and these produce γ-rays in their turn. This disturbing of the surroundings in the measurement of the absorption of n be eliminated by completely enclosing the active source in al shell of the absorbing medium. By using electroscopes or chambers lined with paper or similar light substance we can the disturbing action of the secondary rays formed. This will from the discussion in the following chapter, a knowledge of essential before we can understand in its entirety the pheno- the scattering of γ-rays. Whereas the alteration in wave- ffered by γ-radiation in the scattering process is independent ve-length,† the intensity of the Compton radiation, altered in ering process, depends very markedly on the wave-length. sity of this Compton radiation assumes considerable propor- for rays of wave-length shorter than about 300 X.U.

medical application of γ- and X-rays the radiation intensity ed in so-called röntgen (r) units. The dose at any point is by the air-ionization equivalent of that part of the quantum ich would be transformed into corpuscular energy by absorption

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n in wave-length is given by $\lambda'-\lambda = 24{\cdot}2(1-\cos\theta)$ X.U., where λ = the λ' = the increased wave-length, and θ = the angle between the incident ered ray. The energy of the radiation produced is given by $h\nu' = h\nu - \frac{1}{2}mv^2$, he energy of the original γ-radiation, and $\frac{1}{2}mv^2$ is the energy of the recoil ree by the scattering process.

in an infinitesimal volume of dry air at 0° C. and 760 mm. Hg press situated at that point, divided by the volume of the air, measured cubic centimetres. If the amount of ionization is such that the t charge per c.c. on the ions of one sign would be 1 e.s.u., then the is defined as 1 röntgen (1 r) [3]. In terms of these units the γ-radiat from 1 mg. Ra (RaB+RaC) supplies 8·6 r per hour at a distance of 1 c whereas the unfiltered β-radiation from the same quantity supp 1,720 r per hour.

REFERENCES

The properties of γ-rays are discussed in detail in *Radiations from Radio* *Substances,* by RUTHERFORD, CHADWICK, and ELLIS (Cambridge Univer Press, 1930), and in *Radioaktivität,* by K. W. F. KOHLRAUSCH (Akademi Verlagsgesellschaft, Leipzig, 1928).

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2. FLEISCHMANN, R., and GENTNER, W., *Zeit. f. Physik*, **100**, 440 (1936).
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THE SECONDARY RAYS

UTUAL PRODUCTION OF THE DIFFERENT KINDS OF RAYS)

Nature of the Secondary Rays

xists an extensive interaction between corpuscular rays like the
ınd to a lesser extent the α-rays, and rays of an electro-magnetic
X-rays arise when cathode rays strike the anticathode of
y tube and are brought to rest; analogously, X- or γ-rays are
d when β-rays lose energy in their passage through matter.
d γ-rays have their origin in the nucleus of the atom (cf. p. 101).
turn X-rays and γ-rays knock off electrons or secondary β-rays
e atoms on which they impinge, and provided they have sufficient
these will again liberate secondary X- or γ-rays, and so forth.
l γ-rays that have originated in this way are briefly designated
ry' rays, a term which is also applied to the rays of secondary
roduced by the α-rays. Scattered primary rays also, which are
ficulty or not at all distinguishable from secondary rays, are
unted in with the secondary rays.

ıost important properties of the secondary rays will now be
d.

ndary β-Rays produced by γ-Rays

al velocity of the β-rays excited in matter by γ-rays is indepen-
he intensity of the γ-rays, and to a first approximation also of
re of the material; thus the β-radiation produced by the γ-rays
C is found to possess, independently of the material in which
ited, a full absorption coefficient in aluminium of about 20,
ırresponding half-value thickness of 0·35 mm. On the other
e initial velocity is dependent on the hardness of the exciting
on; the shorter the wave-length of this, the higher is the velocity
esulting β-particles.† The number of secondary β-particles
rtional to the intensity of the absorbed γ-radiation, and in-
vith the atomic weight of the material used.

condary rays are emitted in various directions, but the direc-
he primary rays preponderates, especially for substances of
ıic weight. According as to whether the secondary rays are

ıllowing relation exists between the maximum energy eV of the secondary
luced, and the frequency ν of the γ-rays exciting them: $U_{\max} = eV = h\nu$
In the calculation of the actual energy of the secondary β-rays (photo-
t must be taken into account that, in order to release them from the atom,
nount of work E_s is required, so that $U = h\nu - E_s$.

emitted from the side of the sheet on which the primary rays are i dent, or from which they emerge, we speak of 'incidence' or 'emerge radiation. The intensity of the incidence radiation increases asy totically with the thickness of the material, and reaches half its ma mum value in the case of aluminium for a thickness of 0·5 mm. also increases with the atomic weight of the secondary radiator shown by the data of Table 18.

TABLE 18

Dependence of the Incidence Radiation on the Atomic Weight

Substance	*Intensity of the incidence radiation in relative units*
Lead . .	7
Copper .	4
Iron . .	3·7
Aluminium	2·1
Paper .	1

It is also immediately clear from the above numbers that, as alrea mentioned on p. 57, we can greatly minimize the influence of secondary rays generated in the walls of the electroscope during measurement of γ-rays, by making use of an electroscope constru from paper. Special precautionary measures are still necessary, howe in order to reduce the secondary β- and γ-radiations from the walls the room, from tables, and so on. The intensities of the incidence a emergence radiations are markedly different, as can be seen f Table 19, in which the data have reference to relatively thick she of the secondary radiators. When quite thin foils are used, the em gence radiation is more intense than the incidence radiation, even the heavier elements.†

TABLE 19

Intensity of Secondary β-Rays

Secondary electrons from	*Soft γ-rays*		*Hard γ-rays*	
	Incidence	*Emergence radiation*	*Incidence radiation*	*Emergenc radiation*
C	170	2,280	58	1,150
Al	280	1,810	120	795
S	340	1,575	154	685
Fe	487	1,350	163	560
Cu	558	. .	202	523
Zn	618	1,160	224	485
Sn	1,051	1,170	333	303
Pb	1,723	2,001	497	470

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† In practice we meet with a mixture of incidence and emergence radiat composition of which depends largely on the experimental arrangement used.

econdary β-rays are composed partly of photo-electrons, and f recoil electrons (cf. p. 52). In the production of the former le of the energy of the γ-quantum or photon, reduced by the extraction (cf. footnote, p. 59), is transmitted to the electron, in the production of recoil electrons only a fraction of the energy is handed over to the recoil electron. For hard γ-rays il electrons preponderate. With decreasing hardness of the ıd increasing atomic number of the secondary rayer, however, turns the scale rapidly in favour of the photo-electrons. Using e secondary radiator and X-rays of hardness equal to that of diation of lead, the ionizing action of the recoil electrons only to about 1 per cent. of that of the photo-electrons. Secondary are also emitted from the surface of a solid body, e.g. a metal, is struck by electronic rays. Electrons of tertiary origin also y occur in this process. The number of secondary electrons ıding to each incident primary electron depends on the velocity imary electron, on the angle of incidence of the primary rays, ıe nature and surface condition of the body. The gas content face also has a fundamental influence on the effect. In certain number of secondary electrons emitted may exceed the num- imary electrons absorbed, so that if the body is insulated, it p positively. If secondary electrons are measured along with nitted primary radiation, we may likewise obtain an apparent absorption'. The velocity of the secondary rays does not ssentially either on the material of the secondary rayer or on ty of the primary rays. The tertiary electrons can be distin- rom the secondary electrons by the aid of the cloud-track The cloud droplets, each of which registers an ion, are arranged track of the rays not only in single pairs, but also in groups ıd so on. Such a group indicates that a secondary electron ced 1, 2, or more tertiary electrons. On the average 2 or 3 ectrons result from each secondary electron, when the primary n has a velocity 33 per cent. that of light.

omagnetic Rays produced by Electrons†

produce X-rays of wave-length λ the energy and correspond- y of the cathode rays must be greater the smaller the value ıe greater the 'hardness' of the resulting γ-rays. The greater ble energy of the cathode rays, the more considerable will dness of the γ-rays. If instead of λ we consider the frequency

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een possible to investigate the excitation of X-rays by cathode rays on a r basis than the excitation of γ-rays by β-particles. In view of the close een the two cases and the importance of this class of phenomenon, the X-rays is also briefly treated here.

$\nu = c/\lambda$, where c = the velocity of light, the following relation ho $U = eV = h\nu$, where U is the energy of the cathode rays, V is discharge potential, and h is Planck's constant.† Alternatively, have $\lambda = 12{\cdot}34/V$, when λ is expressed in Angstrom units (1 A.U. = 1 cm.), and V in kilovolts (cf. p. 54). From this relation it follows t the shortest wave-length that can be excited by the aid of a disch potential of 10,000 volts is of magnitude 1·234 A.U.

Whereas the validity of the above discussion is independent of chemical nature of the radiating source, we shall discuss in what foll the influence of the nature of the source on the character of the X-ra tion emitted.

If, for instance, cathode rays impinge on a rhodium anticathod an X-ray tube, an investigation of the X-radiation emitted by it sh the presence, along with a heterogeneous 'white' radiation, of seve sharply defined types of rays, of which the shortest has a wave-len of 0·534 A.U. This radiation is as 'characteristic' of rhodium as D-lines in optics are characteristic of sodium.‡ As required by the ab formula, it ceases to occur as soon as the discharge potential sinks be about 23,000 volts. Further lines of the rhodium spectrum, those of L-group, can only be detected by the use of a vacuum spectrograph. they are so soft that a layer of air 20 cm. in thickness almost comple absorbs them. Fig. 22 (Plate III) shows the L-spectrum of the min thucolite, and was obtained by attaching a small amount of the min to a copper anticathode. In it the absorption edge of bromine can be recognized. As soon as the hardness of the rays falling on the ph graphic plate attains a value sufficient for the excitation of the K-ra tion of the bromine contained in the plate, a sudden increase oc in the absorption of the rays, and hence in the blackening of the pl X-ray spectroscopy further enables us to detect with ease most stances, provided they are present in concentrations not less than 0· 0·001 per cent. The sensitivity is smaller in the case of light atoms, si here a considerable part of the X-rays may be absorbed in the very at in which they are excited, giving rise to photo-electrons ('Auger Effe

The difference between the two types of radiation, the impuls continuous radiation and the characteristic radiation, in respec their distribution of wave-length in the spectrum is most clearly bro out by having recourse to an optical analogy. The impulse radia corresponds to continuous white light, whereas the characteristic ra tion has its optical analogue in a line spectrum.

In the X-ray spectrum we differentiate between the K-, L-, M-

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† Planck's constant $h = 6{\cdot}61 \times 10^{-27}$ erg sec.

‡ Just like the D-line, the strongest rhodium line also consists of a doublet (0·61 and 0·619 A.U.).

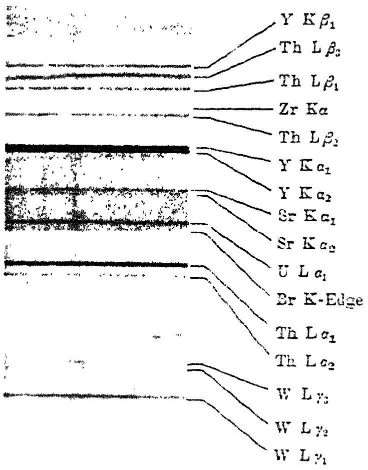
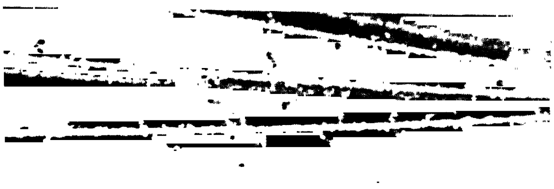


FIG. 22 (p. 62). Emission Spectrum of the Mineral Thucolite.



IG. 27 (p. 67). Tracks of δ-Rays (magnified cloud-tracks of α-particles in helium at low pressure).

P-series, the wave-lengths of which increase as we pass in the der from series to series. The relative positions of the lines in three series are shown diagrammatically in Fig. 23. As far as r at present, there are at most 12 lines in the K-series, and 22 series. These lines can also be divided into different sub-groups; we distinguish only one group in the K-series, we find three -series, five in the M-series, seven in the N-series, five in the and three groups in the P-series. Correspondingly, as we shall ırther detail when we discuss atomic structure, we recognize ıse of the heavy elements 1K-, 3L-,† 5M-, 7N-, 5O-, and 3P- The excitation potential of the cathode rays producing them is for all lines of the same group. The characteristic rays of an

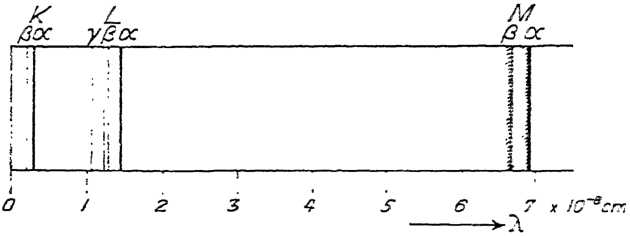


FIG. 23. Wave-lengths in the K-, L-, and M-Series.

ıre related in a simple manner to the atomic number. Thus, equency or 'wave number' ν (= $1/\lambda$) of the strongest line in ies, the following approximate relation, due to Moseley, holds:

$$\sqrt{\nu} = \sqrt{(\tfrac{3}{4}\nu_0)}(N-1),$$

= the atomic number (= 1 for H, 2 for He, 3 for Li, etc.), $1{\cdot}09737 \times 10^5$ cm.$^{-1}$, the well-known Rydberg constant in

from a small systematic deviation, the following formula every line in the characteristic spectrum:

$$\sqrt{\nu} = A(N-B),$$

and B are constants, and N is the atomic number. If we a graph with the atomic numbers of the elements as abscissae quare roots of ν as ordinates, we obtain almost straight lines. Fig. 24, the data of which refer to the strongest lines of the ıd M-series respectively. We shall deal later with important ıs which may be drawn from this regularity. Suffice it to say ıcture that this feature in itself reveals the superiority of the

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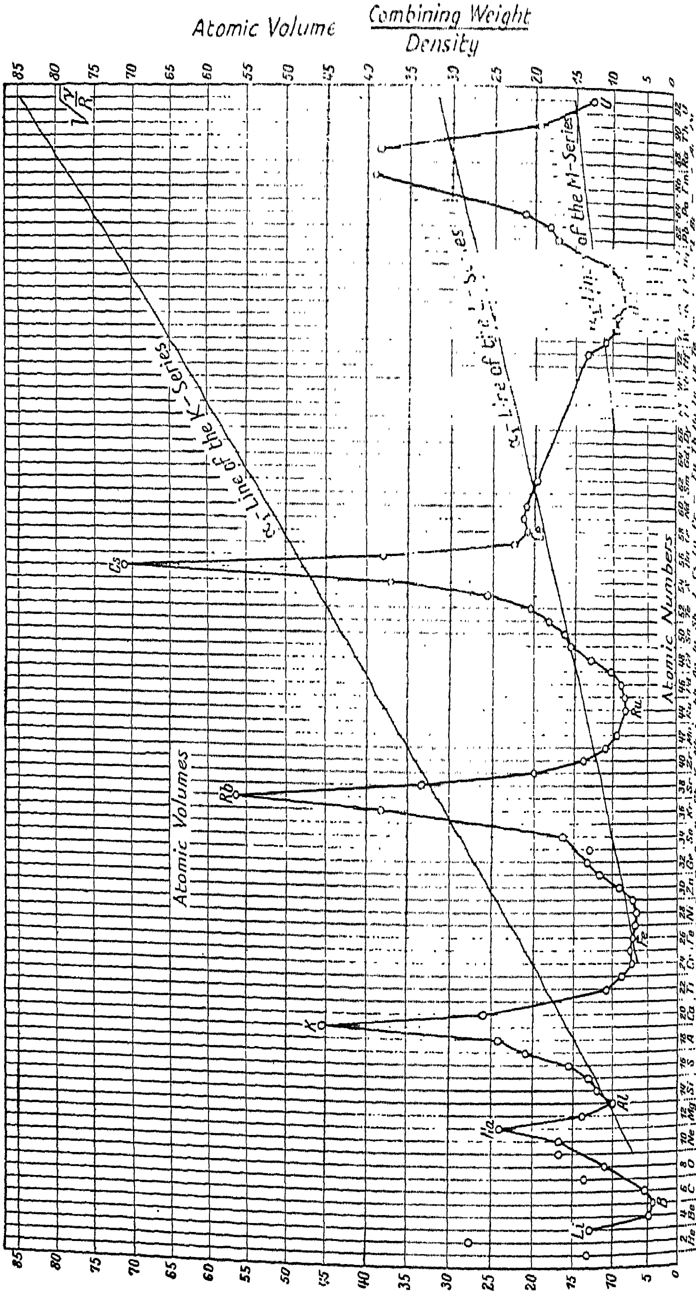
ng with the level that corresponds to the most intense absorption edge, are designated L_1, L_2, and L_3 levels, frequently also L_{III}, L_{II}, and L_I levels


Atomic Volume
Combining Weight / Density
$\sqrt{\frac{\nu}{R}}$
α₁-Line of the K-Series
α₁-Line of the L-Series
α₁-Line of the M-Series
Atomic Volumes
Atomic Numbers
Li
B
Na
Al
K
Fe
Rb
Ru
Cs
U
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0

ıumber over the atomic weight as a means of classifying the elements, for if we choose the atomic weights as abscissae, we)tain straight lines, but irregular ones.

:oduction of characteristic rays results also from the action ;, when their frequency is not less than that of the characteristic frequency (see p. 89). It is the same condition as that which :he occurrence of fluorescence in optics, in accordance with law; a fluorescence radiation cited only by a radiation that er towards the violet end of rum. Since most γ-rays are requency, they are able to ' characteristic radiations of bstances in their passage hem, and this, like the scathe γ-rays and the occurrence ry β-rays, gives rise to a concomplication of the phenoabsorption. It should be l here that the excitation of K-lines requires the same s is necessary for the hardest K-series of the element con- ı the calculation of the least ıecessary to excite a charac- ', we must, in fact, introduce quation on p. 62 not the h of the particular line but always the wave-length of the edge of the group involved, i.e. of the K-group in the present 63). Thus the hardest characteristic radiation known, viz. ıtion of uranium, has a wave-length of 101 X.U. and requires on potential of 115 kilovolts.

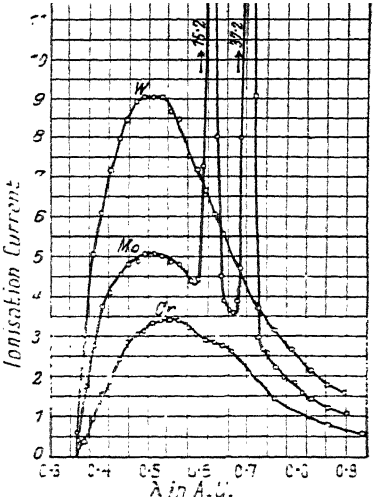


FIG. 25. Distribution of Intensity of Radiation with Wave-length.

t of the spectrum of the continuous or impulse radiation 't wave-length side is determined only by the magnitude of al necessary for its production (see p. 62). The total energy ıtion is proportional to the square of the applied potential, o the fourth power of the velocity of the electrons producing ːr, at constant potential, the total radiation is proportional ic number of the element in which the X-radiation is excited. ıtion of the intensity of the radiation for different wave- ıown in Fig. 25, for the region lying between 0·36 and 0·93 o 930 X.U.). The ionization current, which is plotted as rves as a measure of the intensity of the radiation. The sudden marked rise in intensity in the case of molybdenum is due the fact that the characteristic K-radiation of molybdenum falls the region investigated, whereas the much harder K-radiation of tungsten and the softer K-radiation of chromium fall outside the above range of wave-lengths. The intensity of the emission spectrum thus experiences a sudden increase in those positions where the characteristic ra of the element are excited, and in consequence the emission lines stand out prominently on the more or less blackened background of the photographic plate. In the same way a strongly enhanced absorption of

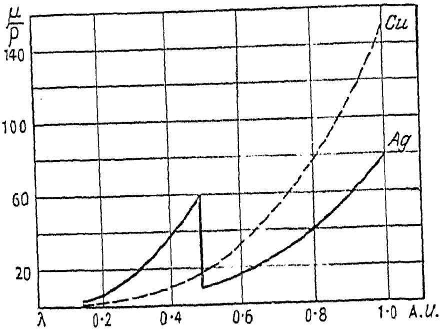


FIG. 26. Variation of Absorption Coefficient with Wave-length.

rays also takes place in definite positions depending on the position the characteristic spectrum. If X-rays are allowed to traverse a sh of molybdenum, it is found that strong absorption suddenly sets in 0·618 A.U. For the case of silver, Fig. 26 shows this sudden increase the absorption, which takes place as the wave-length is gradually reduced. The number of such absorption edges is much less than number of emission lines, and this is due to the fact that, for the excitation of each line, it is not sufficient that the condition $eV = h\nu$ satisfied; the energy used up in the excitation must rather suffice excite the whole group, i.e. all the K-lines. Hence it is that only absorption edge is associated with each group of lines; in consequence of this there exists only one K-edge, and correspondingly only one jump also in the curve for molybdenum (cf. Fig. 26) in the K-region. On other hand, for the softer rays of the L-region there are three jumps in the curve, and these correspond to the three L-absorption edges. they are no longer visible in the figure.

4. Secondary Rays produced by α-Rays. δ-Rays

Secondary β- as well as γ-rays may arise also when α-rays impinge matter. If the α-rays strike solid bodies, slow electron rays or δ-rays are liberated from the place of impact. The number of δ-rays releas

article is practically independent of the nature of the metal and
rection of incidence of the α-particle. On the other hand, the
of δ-rays increases as the velocity of the α-rays decreases. The
of gases in the material bombarded plays an important part
nission of the δ-particles. Thus a surface of zinc, which has
duced by distillation in a vacuum, shows no δ-emission when
ed by α-rays; but when the surface layers absorb gases, δ-rays
ir appearance to a greater and greater extent. The velocities
on of the individual δ-rays vary extensively. The distribution
the curve which represents the frequency of occurrence as a
of the velocity, is, on the other hand, independent of the velo-
e exciting α-rays. Particles with a velocity corresponding to
cur with the greatest frequency. Particles of 15 volts velocity
or about 1 per cent. of the total radiation, but velocities as
,400 volts can also be detected.

equence of the occurrence of δ-rays, the α-ray tracks produced
oud method no longer appear as single lines of fog, but they
e secondary ionization tracks emitted from the main track
ctions (cf. Fig. 27, Plate III).

urrence of δ-rays is largely responsible for the fact that satura-
tained only at high potentials for an ionization current (cf.
to α-rays. The ion density along the track of the α-particle
lly large, so that we may speak of columnar ionization. In
ave ionization not only of the molecules directly struck by
ticle, but the δ-rays released in the process also contribute
tally to the ionization produced.

ticles impinge on atoms of hydrogen, these are ionized and
ry large velocities as a result of the collision, since their mass
e-quarter of that of α-particles. The range of these particles
eral times that of the α-particles producing them. In this
ys' are produced in hydrogen by the α-particles from RaC′,
of these H-rays amounting to about 28 cm. The number of
ns produced by an H-particle per cm. of its path has a value
uarter of that produced by an α-particle of the same velocity.
ns of scintillation observations (see p. 20) it has been possible
small number of particles with a considerably greater range,
us substances are bombarded by α-rays. The observation
rays, which originate in the nuclei of the atoms struck, has
at importance in the elucidation of the nuclear structure of
p. 94 et seq.).

-particles are incident on lead, tin, etc., they are able to
aracteristic X-rays of the elements mentioned, but the in-
the X-radiation produced in this way is very feeble. Thus

from the K-level of zinc only 0·00023 of a quantum of K-radiatio liberated along its track by an α-particle from polonium, and yield in the excitation of L-rays is still smaller. Moreover, a γ-ra tion has been observed to occur during the bombardment of Li, B, F, Mg, and Al with α-rays. The hardness of these rays is of the sa order of magnitude as that of the hardest γ-rays, but their inten is exceedingly small. (Cf. p. 102.)

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A detailed discussion of the properties of the secondary radiations will be in the *Handbuch der Physik*, 2nd ed. (Springer, Berlin, 1933), vols. xxii/2 xxiii/2. X-ray spectroscopy is fully dealt with in *Spektroskopie der Röntgenstr* 2nd ed.), by M. SIEGBAHN (Berlin, 1931); an English translation of the 1st ed was published by the Clarendon Press, Oxford (1925).

VI

THE RECOIL RAYS

n α-particle is emitted from an atom, the latter recoils in the direction in accordance with the principle of action and , just as a gun recoils when a shot is fired from it.

mass and velocity of the projectile are m_1 and v_1, and those of m_2 and v_2, we have

$$v_2 = v_1 \cdot \frac{m_1}{m_2}.$$

n atom of RaA emits α-particles with a velocity of $1{\cdot}69\times10^9$ and is transformed at the same time into an atom of RaB, rojected by virtue of recoil with a velocity of

$$1{\cdot}69\times10^9\times\frac{4}{214} = 3{\cdot}31\times10^7 \text{ cm./sec.},$$

c weight of the α-particle being 4, and that of the RaB atom . The velocity of the residual atom of RaB is considerably hat of the α-particle, but it is sufficient to ionize the air along to act on a photographic plate, etc. As a consequence of the locity of the recoil rays, the number of ions produced by each r cm. of its track is, in fact, markedly greater than and reaches ve times as large as that due to an α-particle. As with the , the ability of the recoil particle to produce these effects denly, the range in air amounting to about 0·14 mm., and 2×10^{-5} mm. Owing to their smaller velocity, the pheno- scattering occurs in a more marked degree with recoil rays α-particles. From the magnitude of the deflexion in a mag- it follows that the recoil atom has an atomic weight of about agrees well with that of RaB, and that it carries a single charge (cf. p. 70).

ve a deposit of RaA on a horizontal metal plate, the atoms α-particles in an upward direction will be projected down- will penetrate the upper layers of the plate; conversely, s that have emitted α-particles in the downward direction jected upwards into the air surrounding the plate. The rable yield of recoil atoms collected after leaving the plate cordingly amounts to 50 per cent.

bility of obtaining individual radio-elements in a pure state the phenomenon of radioactive recoil plays a very important study of radioactivity (see p. 218). In order to be independent of the small range of the recoil atoms, they are collected i electric field, i.e. the preparation is raised to a positive potenti say 100 volts, the negative pole of the battery being connected t insulated plate fixed a few millimetres above the preparation. Ex for a very small fraction the residual atoms are positively charged, hence they are drawn through the air to the upper plate (see Fig. After emission of the positively charged α-particles, the recoil atom at first negatively charged, but when they ionize molecules of the

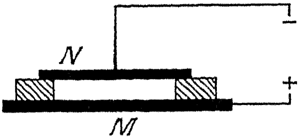

Fig. 28. Arrangement for collecting Recoil Atoms.

rounding air they part with several electrons and so themselves acq a positive charge. An investigation of the deflexion of the recoil a of RaB in a magnetic field has revealed that practically all of t carry a single positive charge, and that only about 0·001 per cen them are negatively charged.

The phenomenon of recoil must also occur during the emission β-particle, but the resulting residual atoms are much more diffic detect than the products of α-recoil. The kinetic energy of the proj particle is here much smaller, and is usually insufficient to prope particle away from the surface of the plate on which the disintegra takes place. It corresponds to the kinetic energy of an equally h singly charged ion that has traversed a potential difference of a tenths of a volt. Nevertheless, it is possible to collect up to 23 per of the RaC atoms which suffer recoil in the disintegration of RaB the application of special precautionary measures. These include w ing in a high vacuum, purification of the initial substance by distilla in a vacuum, deposition of the material used on a polished surface t has been cooled to a low temperature to prevent the volatilizatio the particles.

The photographic detection of recoil atoms is only possible w the gelatine layer of the plates is so thin that the recoil atoms ar brought to rest before they reach the silver bromide.

We meet with a special type of recoil in the phenomenon of 'aggre recoil'. If we deposit polonium electrolytically on a bright meta and place a second foil near to and facing it, we can detect polon also on the second foil after a short time. The explanation of phenomenon is that, during electrolysis, the polonium is not depos

oil in the form of individual atoms, but as aggregates of two
atoms. When one of the atoms of such an aggregate disinte-
ot only the RaG atom resulting from the disintegrated polonium
coil, but the unchanged polonium atoms present in the same
e are projected with it from the foil. Thus when an α-particle
d in the direction of the first foil, the remaining aggregate,
g of a RaG atom and one or more polonium atoms, is projected
irection of the second plate. This phenomenon supplies an
ion of the fact that all objects in the neighbourhood of strong
preparations become contaminated with polonium, even
his element gives off no emanation, and its product of dis-
on is no longer active. Aggregate recoil phenomena can also
ed with preparations in which the polonium was not deposited
ically, but by collecting the active deposit from radium emana-
other radio-elements that emit α-rays show similar effects.
es of the active deposit are also produced in mixtures of
n and air or argon.

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perties of recoil particles are fully discussed in *Radiations from Substances*, by RUTHERFORD, CHADWICK, and ELLIS (Cambridge Press, 1930), and in *Radioaktivität*, by MEYER and SCHWEIDLER Leipzig, 1927).

VII

POSITRONS AND NEUTRONS

A. POSITRONS

POSITIVE electrons are not emitted in natural radioactive proc but the emission of such particles can be detected in the disintegra of different products of artificial radioactivity (see p. 120). aluminium (cf. p. 120, Table 30) that has been rendered active artifi by bombardment with α-rays emits positive electrons or 'positr and gradually loses its activity in the process. The positrons em by aluminium have very different velocities; they show a contin energy spectrum with a limiting maximum energy of about 3×10^6 the most frequently represented energy value being 9×10^5 e.V. mass, charge, and ionizing power of the positron have been foun be the same as those of the electron. Apart from the sign of the ch however, there is found to be a fundamental difference between electron and the positron, for positrons have no permanent existe When they collide with electrons they combine with them, and energy of 10^6 e.V. liberated in the process of union is emitted in the of quanta of γ-rays. In most cases the union is effected with elec at rest, and then two quanta each of energy 500,000 e.V. are em in opposite directions; but there are also processes in which the energy of annihilation is emitted in a single quantum of energy 10^6 Accordingly, the incidence of positrons on matter results in the emis of a γ-radiation (cf. p. 52) which is independent of the nature of absorbing element; in all cases we are concerned solely with the c bination of positrons with electrons of the element under considera Conversely, positrons may be produced by the incidence of hard γ- on matter, e.g. the γ-rays from RaC, the energy of which lies betw $1{\cdot}0\times10^6$ and $2{\cdot}2\times10^6$ e.V. Positrons are also released by the ac of electrons when their energy exceeds 10^6 e.V.

Positrons were first observed in the examination of the cloud tra produced in a Wilson chamber by the cosmic rays, when indivi tracks were found to have been deflected by the magnetic field direction opposite to those due to electrons.

It was found recently that RaC and (ThC+ThC″) emit a very sm number of positrons, to wit, one positron to every 3,000 disintegra atoms. These positrons are not emitted by the nucleus of the dis grating atom, but are the result of secondary processes [1].

B. NEUTRONS

positrons, neutrons do not appear in the course of natural
disintegration processes; on the other hand, they are fre-
served in processes of constrained transformation of the
Thus when α-particles strike beryllium nuclei, beryllium
ned into carbon, and at the same time neutrons are liberated
nce with the equation:

$$^{9}_{4}\text{Be}+{}^{4}_{2}\text{He}={}^{12}_{6}\text{C}+{}^{1}_{0}n.$$

s is described in greater detail on p. 78.
are atomic nuclei which possess no charge, as it were atoms
ent of zero atomic number. Since they possess no charge,
t interact with the peripheral parts of atoms with which
, and hence they do not effect ionization in their passage
air; because of this they cannot be detected by methods
hose used for the other types of rays, already described.
eutrons do interact with atomic nuclei, and by virtue of
ion they can be detected. When neutrons collide with
clei the latter are set into rapid motion, and these moving
be detected, e.g. by use of a cloud chamber. The detection
rons is effected by making use of an electroscope filled
en or lined with paraffin wax, and also by their ability
ut artificial radioactivity (cf. p. 114). If we are faced
blem of deciding whether or not fast neutrons are being
source, it suffices to introduce say silicon in the form of a
to the path of the supposed neutrons, and then after some
he glass plate by bringing it near to a tube counter. Neu-
the silicon nucleus and call forth an artificial radioactivity,
under emission of hard β-rays (cf. p. 116). From the
these readily detectable β-rays we can infer the presence
ns. If we require to detect slow neutrons, iodine, silver,
lysprosium may be introduced into the path of the sup-
s. These elements serve as specially suitable 'receivers'
rons, and the capture of the neutrons brings about in
detectable artificial radioactivity. Another method that
ich used consists in allowing the neutrons to enter an
mber, the walls of which are coated with boron or lithium.
processes take place under the action of slow neutrons:

$$+{}^{1}_{0}n={}^{7}_{3}\text{Li}+{}^{4}_{2}\text{He} \quad \text{and} \quad {}^{6}_{3}\text{Li}+{}^{1}_{0}n={}^{3}_{1}\text{H}+{}^{4}_{2}\text{He}.$$

particles produced in this way ionize the gas contained
on chamber. If the capture of a neutron leads to the
stable isotope and not to a radioactive isotope of the

element concerned, it is then impossible to resort to artificial ra activity for the detection of the neutrons. An example of th the capture of a neutron by lead 206, whereby the stable isotop lead (207) is formed in accordance with the equation:

$$^{206}_{82}\mathrm{Pb}+^{1}_{0}n = ^{207}_{82}\mathrm{Pb}.$$

In such cases the capture of neutrons can be detected by the emis of γ-rays. The incorporation of neutrons into atomic nuclei is als an exothermic process, and the energy liberated is emitted in the of γ-rays.

1. Absorption and Scattering of the Flux of Neutrons

The flux of neutrons is reduced owing to their gradual capture by nuclei of the atoms penetrated; a reduction also arises from e collisions of the neutrons with atomic nuclei, and by nuclear scatte Neutrons suffer elastic collisions in particular with protons, e. water or in paraffin wax, and this leads to a rapid decrease in the en of the neutrons. When the velocity of a neutron is markedly gr than the mean velocity of the molecules of a gas, and it collides w proton, the energy of the neutron is reduced on the average to one of its initial value. Accordingly, after ten collisions with proton mean energy of the neutron will have fallen to one-thousandth original value. Neutrons of energy 4 × 10^6 e.V. are strongly represe in the flux of neutrons emitted by mixtures of radon and bery powder, this being the most familiar source of neutrons. After te lisions such neutrons have on the average an energy of only about e.V., and less than thirty collisions with protons are necessary in ord obtain neutrons with velocities of normal molecular magnitude. The life of such a neutron in paraffin wax is 2 × 10^{-4} sec. [3]. One of the of demonstrating that the slowest neutrons actually have velo comparable with those of gaseous molecules is as follows. It has possible to show that, when paraffin wax is reduced to the tempera of liquid air, slow neutrons suffer a greater reduction of velocity ini they are then able to activate silver more strongly than before. the capture of neutrons by silver and similar nuclei (cf. p. 77) takes more readily the slower the neutrons. The large diminution in en experienced by neutrons when they collide with protons is to be buted to the fact that the mass of a neutron (cf. p. 77) is practi equal to that of a proton, and in consequence of this the transmi of energy from the colliding particle to that struck takes place readily. The velocity of neutrons can also be reduced by their col with the nuclei of other light elements such as carbon or silicon with them the effect is very much smaller. The velocity of fast neu duced by their inelastic collision with heavy atoms, but in the energy given off by the neutrons is utilized to excite the leus, and it is later emitted in the form of γ-radiation.

t follows we shall consider separately the reduction in the st and of slow neutrons, i.e. their absorption and scattering. the cross-sections of light nuclei (cf. p. 79), and we can accord- ılate the reduction in flux which fast neutrons should experi- eir passage through light atoms, on the assumption that the lear cross-section is effective in the scattering.† The values d experimentally agree approximately with those calculated. pass over to heavier nuclei the cross-sections increase pro- Here it is not possible to compare the cross-sections obtained cattering of neutrons with values obtained by other means, ıods which permit the calculation of the cross-sections of s fail in the case of heavy atoms. It is probable that the oss-section resulting from the 'absorption' values of fast ı their passage through the atoms concerned represents the r cross-section. The effective cross-sections for fast neutrons $1{\cdot}6\times10^{-24}$ cm.^{2} (light nuclei) and $5{\cdot}8\times10^{-24}$ cm.^{2} (mercury) ow a fairly regular increase within that range.‡

trons show quite a different behaviour from fast ones. The oss-section in the scattering of slow neutrons is roughly total nuclear cross-section. Hydrogen nuclei alone behave for they scatter very much more strongly than would be om the magnitude of the cross-section of hydrogen nuclei. on in intensity arising from the absorption and scattering by slow neutrons in nuclei is very different from element ınd the effective cross-section varies between $1{\cdot}5\times10^{-24}$ cm.^{2} m and $25{,}000\times10^{-24}$ cm.^{2} for gadolinium. Cadmium, euro- ium, and especially gadolinium have large effective cross- respect of the absorption of slow neutrons, as may be ıble 20. The effective cross-sections are dependent on the he neutrons. In the cases of lithium and boron the con- articularly simple, for here the effective cross-sections are ıportional to the velocity of the neutrons [2]. The large ıs-section of the cadmium nucleus, on the other hand, is ıed for neutrons whose energy does not exceed 1 e.V., i.e. ıtrons of velocity at most 3 to 4 times greater than the locities met with at room temperatures, in accordance

e cross-section is equal to the mass absorption coefficient divided by tiplied by the atomic weight (cf. p. 51).

the cross-section is due mainly to scattering, for only a small fraction is captured in the collision process.

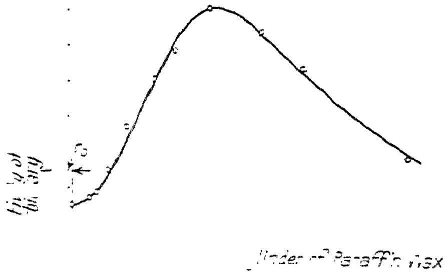
with the kinetic theory of gases. For this reason cadmium is used screening material whenever it is desired to exclude neutrons thermal energies. Neutrons with molecular velocities, though po fully absorbed by cadmium, are only feebly absorbed for examp arsenic. For a particular range of velocity, however, this latter ele manifests a large effective cross-section of about 100 times the nu cross-section, and within this range it is effective to a degree parable with that of cadmium for neutrons with molecular velo Gold, silver, rhodium, iodine, indium, and possibly many other ments likewise possess a very high absorbing power for a limited of velocity of the neutrons. This kind of absorption is generally k as 'resonance capture'.

TABLE 20

Nuclear Cross-sections with respect to Slow Neutrons (*cm.*^{2} × 10

Element	*Cross-section*	*Element*	*Cross-section*	*Element*	*Cross-*
H	48	Co	35	Ba	1
B	500	Ni	15·4	Sm	4,0
C	3·4	Cu	7·4	Eu	3,
N	11·3	Zn	4·7	Gd	25,0
O	3·3	Br	11·8	Dy	1,3
Na	4·2	Y	119	Ir	
Mg	3·0	Mo	7·1	Pt	
Al	1·0	Rh	115	Au	
Si	2·5	Pd	10	Hg	3
Cl	39	Ag	55	Pb	
K	8·2	Cd	3,300	Th	
Ca	11	I	9·4	U	

The production of slow neutrons is effected most simply by sur ing the source of neutrons with paraffin wax [3], the source bei a glass tube containing a mixture of radon and beryllium. B quent collision of the fast neutrons with paraffin wax their velo reduced to molecular magnitude, and these retarded neutrons f diffuse until they either emerge from the paraffin block or are ab by a hydrogen nucleus. Neutrons with molecular velocities can diffuse through a distance of about 2 to 3 cm. in paraffin wax for this reason slow neutrons with the velocity of gaseous mole emerge only from the outer layer of thickness 2 to 3 cm. of a cylinder of paraffin wax. When large cylinders of paraffin wax are the yield of slow neutrons is small, and diminishes further as the ci dimensions are increased. Likewise, if the cylinder is chosen s its radius is less than 2 to 3 cm., a poor yield of slow neutrons is obta since the quantity of paraffin wax does not then suffice to reta fast neutrons adequately. The alteration in the number of slo trons that strike a surface of silver in unit time when the thick ıdrical wax layer surrounding the source is varied follows from eration of Fig. 29 [4]. The slow neutrons are captured by the ıclei, and bring about artificial radioactivity in the silver. The is proportional to the number of slow neutrons incident on r, and in the graph the activity of the silver is plotted in its nce on the thickness of the wax layer surrounding the source



29. Activity induced in silver situated at a fixed distance from the ıtron source, surrounded by wax cylinders of different radius (r).

ıs. The maximum yield is obtained when the thickness of the ıaraffin wax is about 9 cm. If we wish to produce neutrons ediate velocity, we must choose a thinner layer of paraffin ments that show no marked absorbing power for neutrons em to a considerable degree. In experiments with neutrons, scattering effected by the walls of the room may have a influence.

ass of the Neutron

ıtron is not deflected in an electric or in a magnetic field, the hich served for the determination of the masses of α- and are of no avail here. The following method is the simplest accurate for the evaluation of the mass of the neutron [5]. action of γ-rays, neutrons (n) are split off from the atoms of rogen, deuterium (D), in accordance with the equation:

$$^{2}_{1}\mathrm{D}+E_{\gamma}=\,^{1}_{1}\mathrm{H}+\,^{1}_{0}n+E_{\mathrm{H}}+E_{n}.$$

energy E_{γ} of the γ-ray quanta of ThC″ from radiothorium experiments amounts to $2{\cdot}65\times10^{6}$ e.V., corresponding to it of atomic weight,† and the kinetic energies E_{H} and E_{n} ective protons and neutrons produced both amount to .V., the above equation takes the following form:

$$1471+0{\cdot}00285=1{\cdot}00812+0{\cdot}000269+0{\cdot}000269+n,$$

$$\text{or}\quad n=1{\cdot}00890.$$

---

† 1 electron-volt = $1{\cdot}0741\times10^{-9}$ unit of atomic weight.

The smallest amount of energy necessary to split off a neutron fro deuterium atom is 2·1 × 10^6 e.V., and for the atom ^{9}Be 1·6×1 From amongst all atomic nuclei, that of ^{9}Be is found to have the weakly bound neutrons. In the production of neutrons by bom ment with α-rays, beryllium is for this reason to be preferred t other elements, as also when the neutrons are released by the aid γ-rays from radium. On the other hand, when radiothorium is u a source of γ-rays, six times as many neutrons are emitted by deut as by beryllium. The greatest yield of neutrons is attained i bombardment of compounds containing heavy hydrogen (e.g. N by means of positive rays of deuterium.

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VIII

ITUTION OF THE ATOM AND RADIOACTIVE RAYS

aviour of the rays from radioactive substances in their passage matter has been our most reliable guide in the investigation nstitution of atoms; conversely, the theory of atomic structure ed up many points on the origin and nature of the individual rays. Accordingly, we shall now give a short account of the ion of the atom.

Constitution of the Atom

s from the behaviour of α- and β-particles in their passage atoms that the material part of the atom does not embrace of the atom, regarded as a sphere of radius 10^{-8} cm., but is to an exceedingly small space at the centre of the atom, of about 10^{-13} cm.† Moreover, this atomic nucleus is positively The remainder, or practically the whole of the space inside the here is at the disposal of the electrons that revolve round the The dimensions of this electron cloud determine the magnitude m, and the number of electrons in it is equal to the number of y units of positive charge associated with the nucleus. As a atom thus appears electrically neutral.

al number of electrons revolving in the atom, and hence also er of nuclear positive charges, is equal to the atomic number) of the element concerned. The number of orbital electrons for the hydrogen atom, 2 for helium, 3 for lithium, 29 for for platinum, and 92 for uranium, the element of highest mber.

ectrically neutral atom becomes ionized, it assumes either a a negative charge. In the former case the outer electron a definite number of electrons, and in the second case the up one or more electrons from the surrounding matter or ee electrons in the surrounding space. Ionization or chemical ny kind, however, can produce no alteration in the number n the nucleus, and hence these processes are always reversible. bility of all changes in the character of the atom produced l processes signifies nothing else than the long-known law

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e is derived from the magnitude of the deviation suffered by α-particles netrate the vicinity of the nucleus (see p. 95). The radius of the sun is mes smaller than that of the orbit of Neptune; the nucleus of the atom, es in its structure a solar system, is about 10,000 times smaller than the electrons from the centre of the system.

of the conservation of the elements. In the relatively rare cas radioactive processes on the other hand, the nucleus, and hence the system of electrons surrounding it, undergo permanent tra formation. The emission of the rays from radioactive substances is intimately related to this transformation, which, as described on p. involves a complete alteration in the chemical nature of the atom

The stability of an atom built up in the manner indicated can be explained on the basis of classical mechanics and electrodynam In order to understand it, it was necessary to formulate the hypoth that there are certain privileged states of motion of the atom, in w states the atom persists without loss of energy. The energy con of the atom can change only when the atom passes over from one privileged state into another (see p. 90).

For the interpretation of radiation processes it was necessar supplement this hypothesis by a second one, according to whi such a transition is associated with the emission of radiation, the l is always monochromatic, and of frequency equal to the quotien the amount of energy radiated and Planck's constant *h*.

The experimental evidence in support of the view outlined abo so multifarious that it cannot be treated exhaustively here. We only mention the following especially important phenomena: the tering of the α-rays in their passage through matter (p. 31), iso (p. 147), and the emission and absorption of light, X-rays, etc., as are revealed in the spectra of the elements.

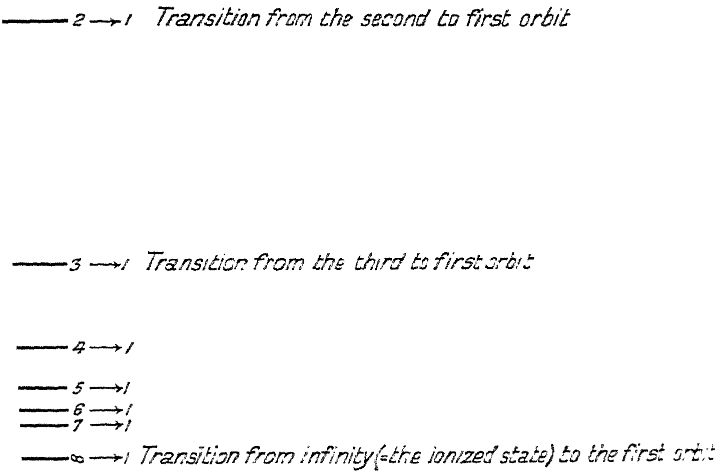
Before we proceed to the question of the origin of the rays from ra active substances, it will be advisable to discuss in somewhat gre detail the structure of the atom in the simplest cases, by first ma use of the original presentation due to Bohr.

2. Structure of the Hydrogen Atom

A hydrogen atom consists of a nucleus, carrying only a single pos charge, and an electron, which, in accordance with the first hypoth mentioned above, always moves in certain permissible orbits. T motion is subject to Kepler's laws, like that of a planet round the which is situated at the focus of the orbit, so that the privileged or of the electron are ellipses.

There is quite a number of such stationary orbits, but one of the unique in that when the electron is moving in it, the atom possesse smallest content of energy. The hydrogen atom can persist permane in this 'normal state', whereas the 'life' of all other stationary st is very short.

According to the second hypothesis mentioned above, a monoc matic pulse of waves is emitted when an electron passes over ionary state to another. In Fig. 30 we see the spectroscopic ences of the return of an electron to its normal orbit from stationary orbit, into which it has passed by virtue of some influence such as bombardment by cathode rays. When the the normal orbit takes place from orbit 2, a spectral line of gth 121 mμ is emitted, whilst if the transition takes place


2 → 1 Transition from the second to first orbit
3 → 1 Transition from the third to first orbit
4 → 1
5 → 1
6 → 1
7 → 1
∞ → 1 Transition from infinity (=the ionized state) to the first orbit

. Spectrum of Hydrogen in the Ultra-violet Region (Lyman Series).

3, a line of shorter wave-length 102 mμ is produced, because ter energy difference between the two orbits, and so on for ransitions. Should the return take place from an infinitely it, a spectral line of wave-length 91 mμ is emitted. This last ivalent to the 'neutralization' of a hydrogen ion, since of converse process of the removal of an electron to infinity the phenomenon of 'ionization'. In the light of the theory ectra, this neutralization process thus appears as a limiting discontinuous quantum states. The above-mentioned lines l lie in the extreme ultra-violet. The lines of the visible hydrogen likewise have their origin in transitions from one rbit to another, e.g. from orbits 3, 4, etc. to orbit 2.

ive distances of the individual stationary orbits from the atom are represented in Fig. 31. The diameter of the first of the atom in its normal state, and is equal to $1{\cdot}06 \times 10^{-8}$ lculation of the orbital radii involves only three universal e elementary electrical charge ϵ, the mass of the electron m, s constant h (p. 62). The same quantities also suffice to calculate the work that is necessary to transfer an electron fr stationary orbit to another. For instance, we can calculate the necessary to remove entirely an electron from the atom, and wh result is expressed in volts (see p. 43), we find the value to be this is the ionization potential of the hydrogen atom.

In the construction of Fig. 31 it was assumed, for purposes plicity, that the electron moves in circular orbits, so that in

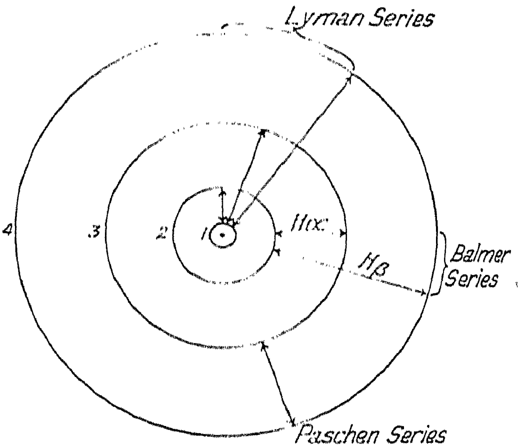
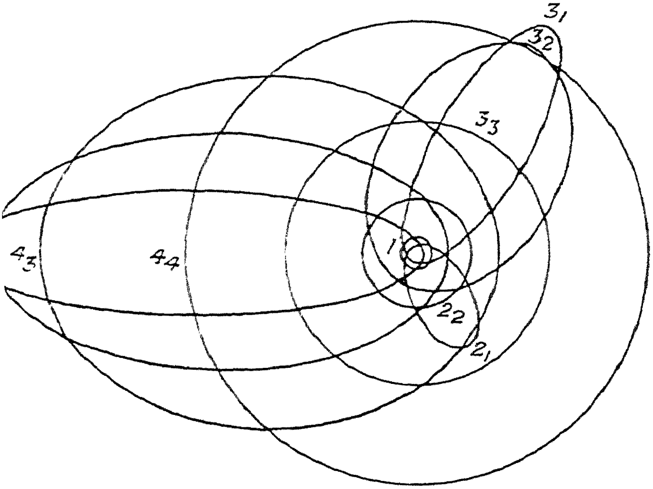


FIG. 31. Stationary Circular Orbits in the Hydrogen Atom.

differentiate between the stationary orbits or to describe the p one number suffices, this being called the quantum number. I to be able to describe the spectral behaviour in all its details, h it was necessary to introduce a second, and later still a third an a fourth quantum number. Even when a motion takes place in s ary elliptical orbits, it is no longer sufficient to characterize the sta orbit by one number; recourse must be had to a second integral to differentiate between the different eccentricities of the orbits. be clear from Fig. 32 that the major axes of the ellipses have the length for orbits which possess the same first quantum number minor axes vary with the second quantum number in such a w the orbit has its greatest eccentricity when the second quantum is equal to unity, whilst the orbit is circular when the first and quantum numbers have the same value.

The same theory which led to our knowledge of the structur hydrogen atom has been applied also to obtain information structure of the other atoms. At the same time, this work was aided by the results of spectroscopic research, of X-ray spectr by investigations on the bombardment of atoms by electrons, chemistry. It has been found that also when several electrons t in the atom, the orbit of every electron is characterized by numbers, in a manner analogous to the possible orbits in gen atom.



IG. 32. Stationary Elliptical Orbits in the Hydrogen Atom.

f Higher Atomic Number

g symbols are used for the principal quantum number n:

K	L	M	N	O	P
1	2	3	4	5	6;

zimuthal quantum number l is characterized by the sym-

s	p	d	f
0	1	2	3.

which appear as single lines in spectroscopes of average ver are found to be double lines or groups of neighbouring xamined with apparatus of high resolving power. In the ription of this multiplicity of spectral lines a further (third) nber is introduced, the physical significance of which is as electrons exhibit a rotation proper to themselves and rred to as 'spin', and this confers upon them the property ets. In the case of a single electron the strength of binding different, according to the direction of the spin. Two ibilities present themselves for the spin, so that for an the same principal and azimuthal quantum numbers there are two different values of the energy of binding, whe doublets in the spectra of the alkalis. If instead of one electron dealing with two mutually interacting electrons, the conditio more complicated, in the first place by the spin, in the manner indi and furthermore by the different possibilities of orientation electron orbits with respect to each other. In this way arise the of the alkaline earths and the still higher multiplets of the complicated atoms.

In strong magnetic fields spectral lines are resolved into compo the theoretical interpretation of which requires the introducti fourth 'magnetic quantum number' m. In a strong magnetic fi resultant vectors of electron spin and orbital impulse experi definite directional quantization. In order to establish the distri numbers of the level with a given principal quantum numb suffices, in the first place, to disregard spin. In this case the nu possible orientations is one for an s-electron ($l = 0$), three for a p-el ($l = 1$), five for a d-electron ($l = 2$), and in general ($2l+1$) for muthal quantum number l. The magnetic quantum number can ingly assume ($2l+1$) different values and we must assign to it whole numbers from $-l$ to $+l$. Table 21 shows the possible co

TABLE 21

Combinations of the Principal, Azimuthal, and Magnetic Quantum Numbers

$n = 1$	$l = 0$	$m = 0$
$n = 2$	$l = 0$	$m = 0$
$n = 2$	$l = 1$	$m = -1\ 0\ +1$
$n = 3$	$l = 0$	$m = 0$
$n = 3$	$l = 1$	$m = -1\ 0\ +1$
$n = 3$	$l = 2$	$m = -2\ -1\ 0\ +1\ +2$
$n = 4$	$l = 0$	$m = 0$
$n = 4$	$l = 1$	$m = -1\ 0\ +1$
$n = 4$	$l = 2$	$m = -2\ -1\ 0\ +1\ +2$
$n = 4$	$l = 3$	$m = -3\ -2\ -1\ 0\ +1\ +2\ +3$

tions of the three quantum numbers n, l, m, without taking int sideration the spin quantum number. Each of these combinations occur in two ways, either with the spin quantum number $+\frac{1}{2}$ o Since the spin quantum numbers have to differ by unity and be in amount, they can only assume the values $+\frac{1}{2}$ and $-\frac{1}{2}$. In th excited hydrogen atom, in the ground state where $l = s = 0$, the horizontal row of Table 21 reveals to us only one possible comb but this is possible in two ways, with the spin quantum numbe or $-\frac{1}{2}$. There are accordingly two kinds of electrons present in atoms. For a p-state of the atom ($l = 1$) there are already le combinations, and so on. Table 22 shows the grouping s in the whole periodic system.

l fixing of the numbers was facilitated by the application principle. According to this, two electrons in an atom can e in all four quantum numbers, and hence the combinations e individual horizontal rows of Table 21 can be realized by o electrons, to wit, one with a right-handed and one with a l spin. The application of Pauli's principle makes it clear

TABLE 22

The Grouping of Electrons in the Periodic System

K	*L*		*M*			*N*				*O*			*P*			*Q*
s	*s*	*p*	*s*	*p*	*d*	*s*	*p*	*d*	*f*	*s*	*p*	*d*	*s*	*p*	*d*	*s*
1																
2																
2	1															
2	2															
2	2	1														
2	2	2														
2	2	3														
2	2	4														
2	2	5														
2	2	6														
2	2	6	1													
2	2	6	2													
2	2	6	2	1												
2	2	6	2	2												
2	2	6	2	3												
2	2	6	2	4												
2	2	6	2	5												
2	2	6	2	6												
2	2	6	2	6		1										
2	2	6	2	6		2										
2	2	6	2	6	1	2										
2	2	6	2	6	2	2										
2	2	6	2	6	3	2										
2	2	6	2	6	5	1										
2	2	6	2	6	5	2										
2	2	6	2	6	6	2										
2	2	6	2	6	7	2										
2	2	6	2	6	8	2										
2	2	6	2	6	10	1										
2	2	6	2	6	10	2										
2	2	6	2	6	10	2	1									
2	2	6	2	6	10	2	2									
2	2	6	2	6	10	2	3									
2	2	6	2	6	10	2	4									
2	2	6	2	6	10	2	5									
2	2	6	2	6	10	2	6									

TABLE 22 (*cont.*)

	K	*L*		*M*			*N*				*O*			*P*	
	s	*s*	*p*	*s*	*p*	*d*	*s*	*p*	*d*	*f*	*s*	*p*	*d*	*s*	*p*
37 Rb	2	2	6	2	6	10	2	6			1				
38 Sr	2	2	6	2	6	10	2	6			2				
39 Y	2	2	6	2	6	10	2	6	1		2				
40 Zr	2	2	6	2	6	10	2	6	2		2				
41 Nb	2	2	6	2	6	10	2	6	4		1				
42 Mo	2	2	6	2	6	10	2	6	5		1				
43 ..	2	2	6	2	6	10	2	6	(5)		(2)				
44 Ru	2	2	6	2	6	10	2	6	7		1				
45 Rh	2	2	6	2	6	10	2	6	8		1				
46 Pd	2	2	6	2	6	10	2	6	10						
47 Ag	2	2	6	2	6	10	2	6	10		1				
48 Cd	2	2	6	2	6	10	2	6	10		2				
49 In	2	2	6	2	6	10	2	6	10		2	1			
50 Sn	2	2	6	2	6	10	2	6	10		2	2			
51 Sb	2	2	6	2	6	10	2	6	10		2	3			
52 Te	2	2	6	2	6	10	2	6	10		2	4			
53 I	2	2	6	2	6	10	2	6	10		2	5			
54 X	2	2	6	2	6	10	2	6	10		2	6			
55 Cs	2	2	6	2	6	10	2	6	10		2	6		1	
56 Ba	2	2	6	2	6	10	2	6	10		2	6		2	
57 La	2	2	6	2	6	10	2	6	10		2	6	1	2	
58 Ce	2	2	6	2	6	10	2	6	10	(1)	2	6	(1)	(2)	
..	..		..		..				..			..			..
..	..		..		..				..			..			..
72 Hf	2	2	6	2	6	10	2	6	10	14	2	6	(2)	(2)	
73 Ta	2	2	6	2	6	10	2	6	10	14	2	6	(3)	(2)	
74 W	2	2	6	2	6	10	2	6	10	14	2	6	4	2	
75 Re	2	2	6	2	6	10	2	6	10	14	2	6	(5)	(2)	
76 Os	2	2	6	2	6	10	2	6	10	14	2	6	(6)	(2)	
77 Ir	2	2	6	2	6	10	2	6	10	14	2	6	(7)	(2)	
78 Pt	2	2	6	2	6	10	2	6	10	14	2	6	8	2	
79 Au	2	2	6	2	6	10	2	6	10	14	2	6	10	1	
80 Hg	2	2	6	2	6	10	2	6	10	14	2	6	10	2	
81 Tl	2	2	6	2	6	10	2	6	10	14	2	6	10	2	1
82 Pb	2	2	6	2	6	10	2	6	10	14	2	6	10	2	2
83 Bi	2	2	6	2	6	10	2	6	10	14	2	6	10	2	3
84 Po	2	2	6	2	6	10	2	6	10	14	2	6	10	2	4
85 ..	2	2	6	2	6	10	2	6	10	14	2	6	10	2	5
86 Rn	2	2	6	2	6	10	2	6	10	14	2	6	10	2	6
87 ..	2	2	6	2	6	10	2	6	10	14	2	6	10	2	6
88 Ra	2	2	6	2	6	10	2	6	10	14	2	6	10	2	6
89 Ac	2	2	6	2	6	10	2	6	10	14	2	6	10	2	6
90 Th	2	2	6	2	6	10	2	6	10	14	2	6	10	2	6
91 Pa	2	2	6	2	6	10	2	6	10	14	2	6	10	2	6
92 U	2	2	6	2	6	10	2	6	10	14	2	6	10	2	6

why the *K*-group can contain only 2 electrons, the *L*-group the *M*-group only 18, and the *N*-group only 32, and why the in the natural classification of the elements contain respective 18, and 32 elements. For if, in the *K*-, *L*-, *M*-, *N*-, etc., gro ate sub-groups (*s*, *p*, *d*, *f*) according to their azimuthal quan- bers, we obtain as the highest numbers that a sub-group can is can be seen from Table 21, p. 84, in which $l = 0 = s$, $l = 2 = d$, $l = 3 = f$):

2 electrons for an *s*-sub-group (taking account of spin),
6 electrons for a *p*-sub-group,
10 electrons for a *d*-sub-group,
14 electrons for an *f*-sub-group.

he *K*-group the azimuthal quantum number is always zero, ne *s*-sub-group is present, in the *L*-group only one *s*- and one ip. and so on. We thus obtain as the maximum numbers of lual groups:

TABLE 23

Maximum Number of Electrons in the Sub-groups

2 in the one-quantum *K*-group
$2+6 = 8$ in the two-quantum *L*-group
$2+6+10 = 18$ in the three-quantum *M*-group
$2+6+10+14 = 32$ in the four-quantum *N*-group

num numbers 2, 8, 18, 32 are the same as characterize the the individual periods in the natural classification of the

ght of the views outlined above we shall now briefly compare of the characteristic X-ray spectrum with that of the optical ra. Whereas, as discussed above, the optical spectrum of an es its origin to an electron from the outer shell of the atom om one possible position to another, the sudden change in electrons in the inner layers nearest the nucleus gives rise uction of the X-ray spectrum. Compared with that on the ons, the action of the nucleus on the inner electrons is so ng that it can be considered as almost solely operative. his circumstance that simple relationships are found between eristic X-ray spectra of the elements and their atomic

her hand, the processes which take place in the outer layers, d from the nucleus of the atom, are scarcely subject to a ence of the nucleus, and for this reason we find here no ion between the nuclear charge and the optical spectrum. of an element in its group is the determining factor for pectrum; thus the spectra of the alkali metals show an imilar type of structure, in spite of their markedly different bers, because the peripheral arrangement of their electrons

One of the most striking differences between X-rays and o rays is to be found in the fact that no absorption lines occur i X-ray spectrum. Thus when white light passes through sodium va the *D*-lines, which are characteristic emission lines of sodiu absorbed by the vapour, and reveal themselves as sharp absor lines in the spectrum. The analogous phenomenon does not oc the case of X-ray lines; the K_α-line of an element undergoes no g absorption by a layer of the same element than the X-ray lines o slightly greater or slightly lesser frequency. The absorption ris denly only when appreciably shorter wave-lengths are used, an the K_α-line is simultaneously emitted. This characteristic X-rad of the elements is also sometimes called 'fluorescent' radiation, b in optics we find a similar behaviour with fluorescent substances, likewise convert light of shorter wave-length into light of longer length.

On the basis of our conceptions of atomic structure this diff becomes clear. Before an X-ray absorption line could arise, an e from one of the innermost orbits of the atom would have to be re into a more distant orbit; but all the orbits near the nucleus hav full complement of electrons, and absorption can only take place the energy corresponding to the incident wave-length suffices to r an inner electron to the periphery of the atom. To supply the nec energy for this purpose, a distinctly shorter wave-length is re than corresponds to the emission lines of the element, in contr the case of optical absorption spectra, for the production of whic only necessary to raise outer circulating electrons to a slightly energy level. But once an electron has been removed from the most orbit to beyond the surface of the atom, in the manner des the resulting gap will be filled by an electron from the second, or or higher orbit, but not from the surface of the atom, and in th arise respectively the emission lines K_α, K_β, and so forth.

The mode of production of the X-ray spectrum is very clearly re in the diagram of Fig. 33. The *K*-excitation consists in the remo an electron from the *K*-group; in the diagram this is indicated b arrow between *K* and the normal state. The resulting gap in the due to the incomplete population of the *K*-shell, may now be fil the transition of an electron from the *L*-level into the *K*-level, an K_α-line is emitted in this way. A transition of an electron fro *M*-level into the *K*-level is accompanied by the emission of the K whereas the L_α-line is emitted by the transition of an electron fro *M*-level into the *L*-level.

Experimentally there are two methods of determining the e difference between the level corresponding to the normal state an ne of them consists in the determination of the excitation of the K-series, from which we obtain the smallest kinetic the colliding electron must have in order to remove an m the K-group; and the other is based on the determination iting frequency' of the K-absorption jump or absorption just suffices, according to Einstein's relation $eV_0 = h\nu$, to ie atom during absorption the same amount of energy as is

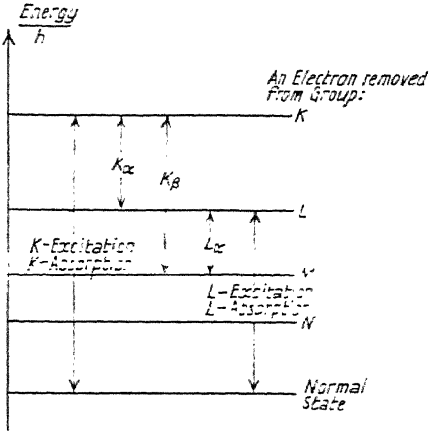


FIG. 33. Production of the X-ray Spectrum.

an electron of velocity V_0 volts. (For information on the vels and lines cf. p. 63.)

Mechanics and Wave Mechanics

y to differentiate between nuclear properties (mass of the radioactivity, etc.) and peripheral or electron properties the chemical behaviour of the elements is determined by id strength of binding of the outer electrons in their atoms; optical spectral lines, X-ray lines are due to quantum more deeply seated levels of the electronic shell of the and other fundamental facts were responsible for the of the model of the atom already described and went with its development. In spite of these facts, however, it essary to replace the atomic model by conceptions of a ature, first, in order to be able to interpret more complifor the mathematical treatment of which the former d failed, and, secondly, in order to avoid difficulties of an l nature. The advance took place along two different quantum mechanics and wave mechanics. In quantum

mechanics the course followed was one indicated by the princ
correspondence, whereas wave mechanics was developed fro
initial conception that the behaviour of electrons must be descr
a dualistic manner. In the latter case, not only the corpuscular
of electrons comes into evidence, but they also possess properti
can only be grasped by their theoretical treatment as waves (m
waves).

The principle of correspondence may be stated as follows: The
changes in the atom do not take place continuously, but ste
The development of the steps is very marked when the energy ch
take place between low quantum states, and as a rule the emis
short waves with large values of $h\nu$ is associated with these chang
when we pass over to higher and higher quantum states, with a
sponding diminution of $h\nu$, the development of the steps degen
in increasingly greater measure. Complete degeneration of the
however, is synonymous with a transition from the quantum-theo
to the classical domain, in which the processes do not occur in
but in a continuous manner. Classical physics is thus revea
a limiting case of quantum physics.

In quantum mechanics we refrain from stating the positi
velocity of the electrons in the atom. Instead of this we make
directly observable quantities for the characterization of the st
the atom, to wit, the frequencies and intensities of spectral lines
resonators), as well as the energy levels of atoms as establis
experiments on electron collisions. The relations obtained in th
embrace both the processes to be described by the quantum
in which the quantum of action unavoidably occurs, and also th
cesses to be described by classical theory, in which the existen
quantum of action cannot be observed. The wave-mechanical vie
is rendered more intelligible by reference to the theory of light.

Light, in addition to having wave properties which are
say in the phenomena of diffraction, has also corpuscular pro
which manifest themselves in the photo-electric effect, wher
quanta or photons are the effective agents. In the case of electr
sequence is reversed, for wave mechanics ascribes to them no
corpuscular properties, but also wave properties. From this p
view matter, or the electrons and protons composing it, a
resolved into waves. In wave mechanics a vibration law is form
for the atom which is quite similar to the law of the mechanical
tions of strings. But here we are not dealing with the motion of m
particles, but with that of an abstract quantity called the Schrö
ψ-function, which is only mathematically intelligible. The prob
that an electron will be situated in a particular position at a

rtional to the square of the magnitude of ψ in this region. ted for the most part to a single region (as say in the case l electron), we can assume with a probability bordering hat the electron will also be found in this confined region. are dealing with an electron in the atom, e.g. the electron en atom, the ψ-waves are distributed over the whole atom, on cannot be localized at a definite place in the atom, but ill be more probable at certain places than at others. nechanical viewpoint is also of great importance in the activity, for it makes the process of disintegration more indicated on p. 98.

tical Appendix to the Chapter on Atomic Structure

r the motion of an electron and of a positive nucleus, the relative to that of the electron can be assumed to be , and for purposes of simplicity let us restrict ourselves its.

's law the force of attraction between the nucleus of an electron of charge ϵ amounts to $\frac{N\epsilon^2}{a^2}$, whilst the equal directed centrifugal force has the value $\frac{mv^2}{a}$, where m ass of the electron, v its velocity, and a the radius of it. Such an atom, built up after the manner of a plane-ll hold together when

$$\frac{N\epsilon^2}{a^2} = \frac{mv^2}{a} \tag{1}$$

f series spectra requires that the angular momentum tron in the stationary orbits cannot assume arbitrary st always be an integral multiple of $\frac{h}{2\pi}$, i.e.

$$mva = \frac{nh}{2\pi}, \tag{2}$$

le number.

equation (2) with equation (1) we can calculate the it of the electron, its velocity, and also the work (W) arate it completely from the atom, or to remove it to onize' the atom. Moreover, we can also calculate from n frequency (ω) of the electron in its stationary orbit.

$$a = \frac{n^2h^2}{4\pi^2N\epsilon^2m}, \tag{3}$$

$$v = \frac{2\pi e^2 N}{hn},$$

$$W = -\tfrac{1}{2}mv^2 + \frac{Ne^2}{a} = \frac{2\pi^2 e^4 m N^2}{h^2 n^2},$$

$$\omega = \frac{4\pi^2 m e^4 N^2}{h^3 n^3}.$$

On the lines of the theory described, the emission of spectr takes place when the electron jumps from one of the orbits perm by the quantum hypothesis into an orbit of lesser energy situated the nucleus, e.g. from the n_1th orbit to the n_2th orbit. If ν den frequency of the spectral line, and W_n the energy content of the in the state n, then

$$\nu h = W_{n_2} - W_{n_1}.$$

For an arbitrary atom we have

$$\nu = \nu_0 N^2 \left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right),$$

where $\nu_0 = \dfrac{2\pi^2 e^4 m}{h^3} = 109{,}737$ (Rydberg's constant) $\times 3 \times 10^{10}$, is the atomic number of the element. For the frequency of the ly lines (Balmer series) we obtain

$$\nu = \nu_0\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right) = (n_1 - n_2)\cdot\nu_0\cdot\frac{n_1+n_2}{n_1^2\,n_2^2}.$$

When n_1 and n_2 are large compared with their difference we $n_1 = n_2 = n$ in the last factor, and by taking account of equa we obtain for the frequency

$$\nu = (n_1 - n_2) \times \frac{2\nu_0}{n^3} = (n_1 - n_2)\omega.$$

From this we see that there exists in the region of large valu a quantitative relation between the revolution frequency a frequency of the radiation, i.e. a 'correspondence' between th and the motion of the electrons in the atom in the region quantum numbers. The harmonics in the radiation correspon $(n_1 - n_2) > 1$, however, are only present when the motion of the is elliptical, and not when it is circular.

If we associate a material wave with every particle, then th nexion between the frequency of this wave (ν) and the mass (m) is $h\nu = mc^2$, where c = the velocity of light, and the velocity of p tion of this wave is $\mu = \lambda\nu$. Since the product of the mechanical

ticle and the velocity of propagation (μ) of its associated
, we obtain

$$\lambda = \frac{c^2}{v\nu},$$

account of the first equation, we deduce

$$\lambda = \frac{h}{mv}$$

wave-length λ of electrons with a velocity of about one-
ight is of approximate magnitude 10^{-9} cm., and of slow
as are emitted by luminous heated wires about 10^{-7} cm.
iental equation of wave mechanics (Schrödinger's differ-
n) is:

$$\Delta\psi + \frac{8\pi^2 m}{h^2}(E - V)\psi = 0,$$

tes the total energy and V the potential energy of the

ued, finite, and continuous solution of the differential
nd only for particular values of the parameter E which
equation, and these are called the 'proper'- or 'eigen'-
ifferential equation. The evaluation of the eigen-values
ial equation thus supplies the required quantum energy-
s way we obtain for the energy of a linear harmonic
reement with experimental evidence,

$$E = (n + \tfrac{1}{2})h\nu.$$

accordingly always an odd multiple of half an energy-

hereas this energy should be an integral multiple of a

ement ($h\nu$) from the viewpoint of considerations based

els. The series of possible energy-steps is thus $\frac{h\nu}{2}$, $3\frac{h\nu}{2}$,

on the earlier mode of consideration the series of steps

$2h\nu$, and so on.

IX

THE ATOMIC NUCLEUS

1. The Constituents of the Nucleus

As discussed in Chapter VIII, it follows from the large defle individual α-particles from their rectilinear path in their p through atoms, that the positive charge responsible for their de is situated at the centre of the atom, and that the atomic nucleus is the carrier of this charge, occupies an extremely small space atomic nucleus contains the positively charged α-particles which the atom in the process of disintegration. β-particles are also e by the nucleus. This follows from the fact (p. 154) that the ex chemical and spectral changes experienced by the atom in conse of the emission of an α-particle $(++)$ are entirely annulled by t of two β-particles $(--)$, a phenomenon that admits of no explanation than that the α- and β-particles are expelled from the part or the nucleus of the atom. It should be noted, however, t the process of atomic disintegration only the primary β-particles ate directly from the nucleus. The secondary β-particles, whi produced during the passage of primary β-, as well as α-, γ-, or rays through the atoms, originate in the electron cloud surro the nucleus, just like the electrons that are involved in the phen of ionization or in other chemical processes. Thus the β-rays th emitted along with the α-rays from radium, radiothorium, and actinium have their origin exclusively in the electron shell of the (see below).

The α-particles, however, are not the ultimate bricks of whi nucleus is composed, for in the process of the artificial disrup atomic nuclei protons, and in other cases neutrons, are ejected the nuclei. We must regard these protons and neutrons as the ult constituents of the nuclei, and consider the α-particle as a li 'molecule' of the 'nuclear atoms' possessing especial stability, an om the union of 2 protons and 2 neutrons. If we make this as we need no longer assume that electrons are present in the the nuclear or primary β-particles that we observe are produced diately before their emission by the transformation: neutron ton+β. The atomic number expresses the number of protons nucleus, whereas the number of neutrons in a particular nuc obtained by subtracting the atomic number from the integer the atomic weight. Isotopes accordingly differ in the number trons contained in their nuclei, the simplest case being that cleus of which consists of a single proton in association n. Even though α-particles are not to be regarded as the ituents of the nucleus, they play a very important part re. In the spontaneous nuclear decay of radioactive articles are frequently ejected, but never protons, and se mass is a multiple of 4 we never observe disruption subjected to the influence of α-particle bombardment. ility of the α-particle is explained by the comparatively ass entailed in its formation from protons and neutrons, h is of a strongly exothermal nature.

ect method of evaluating the nuclear charge (see p. 32) s to measure the scattering which α-particles experience through its atoms: but the most convenient way is the he nuclear charge from the wave-length of characteristic the basis of Moseley's relation (see p. 63).

on nuclear structure is obtained mainly from the study : (*a*) the scattering of α-particles (and in part also of heir passage through atoms; (*b*) α-particles of long range ucture of the α-rays; (*c*) the wave-lengths of the penewhich leave the atom in the disintegration process; n of the atom; (*e*) artificial radioactivity; (*f*) the deviaers of the mass of the isotopic types of atom; (*g*) the ncy distribution of the elements.

Force in the Neighbourhood of the Nucleus

ion of the scattering of α-particles (cf. also the discussion) a strong pencil of α-particles of definite velocity is a thin sheet of the scattering substance, and by means ounts the number of particles deflected through say ed. As a rule, for every 10^5 incident particles about one is observed. By variation of the velocity of the incie dependence of the scattering on the energy of the determined. If the electrostatic repulsion between the nd the positive α-particle is consistent with Coulomb's xpected that the number of scattered α-particles will ortional to the square of their energy. The scattering atoms of the elements which lie between uranium (92) s found to be in accord with this expectation.

stance of approach of an α-particle to the nucleus of t be smaller than the radius of the copper nucleus, radius of the copper nucleus would have an influence stribution of the deflected α-particles. Thus the disproach of an α-particle to the nucleus yields the upper limit for the radius of the copper nucleus, and this is found to b 10^{-12} cm. If we consider the case of a uranium nucleus instea copper nucleus and use the fastest α-particles, we find for the d of nearest approach of the α-particle to the nucleus and hence upper limit of the radius of the uranium nucleus the value 3×10

Should the α-particle penetrate into the nucleus of the ato validity of Coulomb's law must cease and in place of it another be effective. The occurrence of a different law of force from Coulomb in the immediate neighbourhood of the nucleus, is ob in the investigation of the phenomenon of the scattering of α-pa by lighter atoms such as magnesium or aluminium. For ver α-particles we find here also only a small deviation in the num scattered particles from the theoretical value calculated on th of the validity of Coulomb's law; but when the velocity of the ticles is increased we find at first a marked diminution and i increase in the number of scintillations observed experimental the number observed is always less than that calculated theor In Fig. 34 the ordinates represent the numbers of scintillations expressed as percentages of the values calculated theoretically, the abscissae represent the reciprocal values of the energy of the α-particles, for the case of aluminium and for a scattering 135°. The broken line represents the results for gold as the sca substance, and here the value established experimentally amo 100 per cent. of the value calculated, since Coulomb's law holds strictly for the approach of α-particles to heavy nuclei.

The anomalous scattering shown in Fig. 34 for the case of alu and other light atoms must be interpreted by assuming that f approach to the lighter nuclei a force of attraction is superposed Coulomb force of repulsion, the observed effects being due to th resultant from these two components.

Apart from that described above, there is yet a second met calculating the magnitude of the nuclear radius, to wit, from th city of the α-particles emitted. If we assume that an α-par its expulsion from the nucleus is released from the surface wi velocity and is then repelled in accordance with Coulomb's law, w both the α-particle and the residual nucleus are to be regarded a charges, we can then calculate the required nuclear radius in a manner (law of potential) from the energy of the α-particle ob experimentally.† For the uranium nucleus we obtain in th $r \geqslant 6{\cdot}5 \times 10^{-12}$ cm., whereas the above-mentioned deflexion exper quite different value $r \leqslant 3{\cdot}5 \times 10^{-12}$ cm. Thus when we e behaviour of α-particles in the process of scattering by the h that when they escape from the nucleus, we are led to results. This contradiction manifests itself also in another we shall consider in what follows. In order to explain the of scattering we must assume the existence both of a repul- attractive force, of which the former predominates at larger d the latter at smaller distances from the centre of the

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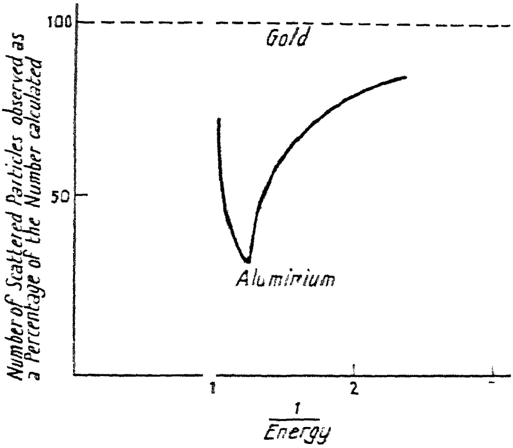
† The energy $E = \dfrac{2e(Z-2)e}{r}$, where r = nuclear radius, e = charge, Z = atomic number.



ion from Coulomb's Law near the Nucleus. Scattering of α-Particles through 135° by Aluminium and Gold.

e plot the potential energy of an α-particle in its depen- istance from the centre of the nucleus, we obtain Fig. 35. of the curve corresponds to the distance from the centre for which the attractive and repulsive forces just balance Within this distance the attractive forces are the deter- and the potential can assume a negative value, whereas ances from the nucleus the potential due to the electro- minishes with increasing distance. On the basis of classi- e can calculate the potential at a distance of 5×10^{-12} cm. e of the nucleus, and for uranium this works out to be volts. Since the fast α-particles possess energy of this y should be in a position to penetrate into the nucleus atom. The phenomenon of scattering, however, shows the case, and that α-particles are prevented from pene- nucleus. It is possible to eliminate the contradictions e turn our attention to the wave-mechanical mode of ribed on p. 89 et seq. Considerations that have been undertaken on this basis lead to a curve whose maximum lies nearer to the nucleus than that of Fig. 35 ($0{\cdot}7\times10^{-12}$ cm. insta 5×10^{-12} cm.). Correspondingly, the maximum protective pot lies very much higher, at 30 million volts instead of at 5 million and falls off very rapidly in the direction of the nucleus. The n is thus protected by a barrier at an exceedingly high potentia the basis of classical ideas no α-particle should be able to surmou barrier in either direction, and if α-particles are emitted from the at all, they ought to escape with a markedly higher energy 30×10^6 volts) than that found from experiment. However, if w

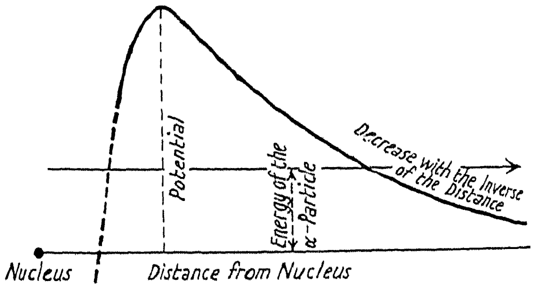


Fig. 35. Variation with Distance of the Potential Energy of an α-Partic in the Field of the Uranium Nucleus.

use of the ideas of wave mechanics, it is possible for an α-parti the wave system with which we identify it, occasionally to vac nucleus, without having to surmount the potential barrier. Fro viewpoint of classical mechanics the particle will never be a escape (i.e. surmount the barrier); wave mechanics, on the other concedes a finite probability of escape through the thin barrier greater the energy of the α-particle and the thinner and lower the through which it passes, the greater will be the probability of its In this way arises a close connexion between the energy of an α-p and the decay period of the element emitting it. This is the rela Geiger and Nuttall, which we shall discuss on pp. 105 and 146.

3. Energy Levels of Atomic Nuclei

We have seen on p. 80 et seq. how the idea of energy levels was with the greatest success in the explanation of the structure extra-nuclear part of the atom. In what follows we shall disc considerations that have led us to assume the existence of energ also in the atomic nucleus, and the nuclear energy level scheme have been obtained.

e most important observations which led to the assumption rels in the nucleus was the result that not all the α-particles itted by the nuclei of certain radio-elements have the same in the case of the α-particles from ThC or AcC (see p. 26). dividual radio-elements other sharply defined lines occur the main line in the velocity spectrum of the α-particles hem. Thus the following five groups of α-rays are found in ectrum of ThC (Table 24). From the figures entered in the

TABLE 24

Energies of the α-Ray Groups emitted by ThC

Group	*Energy in e.V.*
α_1	$6{\cdot}201 \times 10^6$
α_2	$6{\cdot}161$,,
α_3	$5{\cdot}873$,,
α_4	$5{\cdot}729$,,
α_5	$5{\cdot}709$,,

that of the α-rays emitted in the transformation of ThC ly part of them are ejected with the maximum energy of , the remaining groups having a smaller energy content. e between these latter energy values and $6{\cdot}2 \times 10^6$ e.V. is ie resulting ThC″ nuclei. Accordingly, some of the ThC″ surplus content of energy, so that from the viewpoint ls they are in an excited state. From the fact that there rent groups of α-particles with a smaller energy content imum we can conclude that there must be four different ation in the nucleus of ThC″. There will be an additional a normal energy content, and this will exist in all ThC″ have been produced from ThC after the emission of an nergy $= 6{\cdot}2 \times 10^6$ e.V.

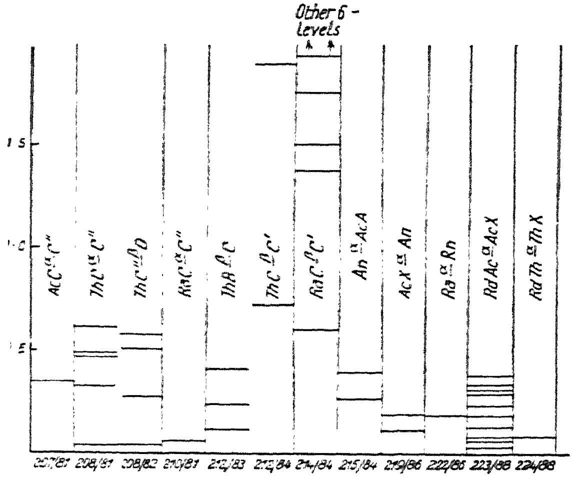
tes have only a limited life, and we should expect that rplus of the excited nuclei will gradually be emitted in ays, in a manner analogous to the production of spectral l spectroscopy (p. 81). This is just what happens, for rays, and in the spectrum of these rays we find a series he frequencies to be expected. Thus from the results of le we should expect an amount of energy given by $= 0{\cdot}040$ million e.V. to be liberated in the transition from hC″ nucleus to the ground level (level 0): this amount of tually appear in the form of γ-rays in the spectrum of tted by ThC″. Likewise in the transition from level II so on, in the nucleus of the ThC″ atom, the quantities of energy liberated reappear in the form of lines in the resulting spectrum, as may be seen from Table 25.

TABLE 25

Energy Differences between the Groups of α-Rays emitted by ThC Energies of the Lines in the γ-Ray Spectrum of ThC″ (Energies in 10

Transition between levels	*Energy difference of the α-ray groups*	*Energy of the γ-line*
$L_I - L_0$	0·040	0·040
$L_{II} - L_0$	0·328	0·327
$L_{III} - L_0$	0·472	0·471
$L_{II} - L_I$	0·288	0·287
$L_{III} - L_I$	0·432	0·432
$L_{IV} - L_I$	0·452	0·451

Also in the case of a β-ray disintegration it is very that the resulting nucleus is in an excited state, and in most ca- energy surplus contained in the excited nucleus is radiated in the of γ-rays, the nucleus passing over into the normal state. No this state has been reached, when we are dealing with a nucle emits α-rays, does the emission of an α-particle occur. Very infrequ however, we are presented with another picture. Here the nuclei are left in a highly excited state after the emission of β-particles first emit γ-quanta, but the energy of excitation is added to the of the normal α-particles, so that more energetic α-particles of range are emitted in place of those of normal range. Thus the α-particles from RaC′, which is produced by β-disintegration from have an energy of 7·68 × 10⁶ e.V., but the emission of every 10⁶ par of normal range is accompanied by the emission of about 22 par of long range. A more detailed investigation has shown that particles of long range are distributed among some 12 groups of dis energy content. Now we have already seen that the energy α-particles of long range is due to the fact that the energies of exc of the nuclei are added to the energy of the normal α-particles, wh may regard as being emitted from the normal or ground level nucleus. In view of the fact that there are thus 13 velocity gr α-particles, we can deduce the initial existence of at least 13 energy in the nucleus of RaC′. In the γ-spectrum of RaC′ there are a num lines which correspond to the differences of many of these energy and this can be regarded as a further argument in favour of the ence of such levels. In order to be able to interpret all the lines γ-ray spectrum we must assume the existence of two additiona in the nucleus of RaC′. These are the considerations which hav the scheme of nuclear levels represented in Fig. 36. The mass ımber of the relevant nucleus are given for each system ell as the radioactive disintegration to which the succeedwes its excitation. Nuclei of different mass number are vertical lines.



cheme of Energy Levels of different Nuclei, obtained by the Analysis of the Fine Structure of α-Rays, of the Long-Range α-Rays, and of the γ-Rays.

scussed above have reference to nuclei whose state of w. Under the action of neutrons it is possible to obtain iergy levels. When a neutron is taken up by a nucleus ount of energy is liberated, to wit, the energy of binding which usually amounts to some 7 to 8 × 10^6 e.V. This appears as energy of excitation of the newly created then gradually emitted in the form of γ-radiation. Exvealed an extraordinarily large number of nuclear levels egion; they are accounted for by the large number of ients (neutrons and protons) involved in the building er nuclei [1].

ıe β- and γ-Radiations

gration of substances with emission of β-rays each tom emits one β-particle. The emission of γ-rays is associated both with β- and with α-ray disintegration. pass through the electron shell of the atom they release ticles, so that these do not originate in the nucleus. In iumber of secondary β-particles exceeds the number of cles, which have their origin in the nucleus. By the the deflexion of β-rays in a magnetic field, line spectra of the rays have been observed, but they are of secondary origi way of showing this is to allow γ-rays from various radio-eleme fall on different substances and to investigate in a magnetic fi energies of the secondary β-rays liberated from the substance this means it is possible to produce in foreign atoms the magnet spectra which otherwise are produced in the shells of the atoms emit the β-rays. Substances like radium, radiothorium, and actinium are α-rayers, but in spite of this they exhibit a ma β-spectrum. This fact supplies us with the most direct proof th magnetic β-spectrum is of secondary origin.

The connexion between the energy of the γ-impulse and that β-particles ejected from the electron groups of the atom is as f The energy of the ejected β-particle is equal to the energy (hν γ-impulse less the work which must be performed in order to relea electron from the electron group involved in the process. This will be different for the various groups from which the electron i released. Let us consider, for example, the very simple spectr radium. There are three β-lines present in this spectrum an energy values are $0{\cdot}876 \times 10^5$, $1{\cdot}720 \times 10^5$, and $1{\cdot}856 \times 10^5$ e.V. Th two differ in energy by $0{\cdot}844 \times 10^5$ e.V., and the last two by 0·13 e.V. From these values it follows that the γ-quanta which lea nuclei liberate secondary electrons from the K-, L_{I}-, and M_{I}-le the radon atoms resulting from the disintegration of atoms of ra since $0{\cdot}844 \times 10^5$ is almost equal to the difference between the of separation ($0{\cdot}981 \times 10^5$ and $0{\cdot}180 \times 10^5$ e.V.) of a K- and of electron, whereas $0{\cdot}136 \times 10^5$ e.V. is the difference between the w separation for an L_{I}-electron and for an M_{I}-electron ($0{\cdot}045 \times 10$ all for an atom of radon. The values for the works of sepa are known from X-ray spectroscopic data (cf. p. 59). The impo of these results lies in the fact that as soon as we know the of the β-ray produced and the work necessary to separate i its particular level, we can immediately obtain the energy γ-ray emitted by the nucleus, which is simply the sum of the quantities. In some cases this is the only method of evaluatin energy of the γ-ray. The value of the energy of a γ-ray from ra $1{\cdot}89 \times 10^5$ e.V. In general it is necessary to assume that several dif γ-rays are emitted from the nuclei of a radioactive substance, in to be able to interpret the lines of the secondary β-spectrum. be seen from Table 26 that the γ-spectrum of RaC consists of

It was at one time assumed that the γ-ray in its passage th the electron shell gives rise to photo-electric effects, and in th produces the discrete groups of β-rays. But it has been shown th intensity of the β-ray groups is much too large to be e -lained

TABLE 26

γ-*Ray Lines of RaC* (83)

Levels from which the β-rays originate	λ (*in X.U.*)
L_I	209·5
K L_I	44·9
K L_I	37·2
K L_I	31·7
K L_I	28·8
K	24·5
K L_I M_I N_I	20·2
K	16·0
K	13·1
K L_I M_I N_I	10·92
K L_I	9·89
K	8·89
K L_I M_I	8·66
K L_I	6·94
K L_I	5·57

Assumed works of separation of an electron for the element 84 (*e.V.*)

$K = 0{\cdot}928 \times 10^5$

$L_I = 0{\cdot}168 \times 10^5$

$L_{II} = 0{\cdot}161 \times 10^5$

$L_{III} = 0{\cdot}135 \times 10^5$

$M_I = 0{\cdot}041 \times 10^5$

lectric effect, and in many cases there is a very rich
s liberated from the shell of the atom by the γ-rays.
of ThB the γ-line of wave-length 51·2 X.U. produces
ns from the K-level of more than 25 per cent., and in
-radiation from RaD a separation yield of more than
been established for all the levels. The γ-lines that
rgy are those of energy $26{\cdot}5 \times 10^5$ and $22{\cdot}2 \times 10^5$ e.V.,
ely from ThC″ and RaC′, whereas the softest γ-lines are
and ThC″ with respective energy values $0{\cdot}32 \times 10^5$
., as obtained from the magnetic spectrum of the rays.
tted in the form of γ-radiation in the process of nuclear
n be determined either calorimetrically or by the
he ionization produced by the γ-rays. The amount
per hour by 1 gm. of radium is 25·5 calories, and of
are to be attributed to the γ-radiation emitted by
of the total secondary β-radiation being included in
In the calorimetric method of determining the γ-ray
ng points should be noted: (*a*) the effect of the α-radia-
; (*b*) the γ-rays are very penetrating; and (*c*) it is
te the effect of the γ-radiation from that of the
these reasons the calorimetric method is less satis-
onization method. Thus it is found that the γ-rays
f Ra(B—C) equivalent to 1 gm. of radium produce
ons per second in air, and since the energy required
f ions in air is 32·5 e.V., it follows that the quantity

of energy radiated in the form of γ-rays from this amount of Ra is 8·8 calories per hour. The mean value of the energy emitted form of γ-radiation during the disintegration of a RaB atom to with the succeeding product is $1{\cdot}86 \times 10^6$ e.V.

5. The Continuous Spectrum of β-Rays

The β-rays emitted by one and the same radio-element, the of which disintegrate by ejection of β-particles, have velociti vary over a wide range. We are here confronted with a con spectrum, in contrast to the line spectrum shown by the resol a magnetic field of β-particles liberated from the atomic shells disregard its very feeble γ-radiation, RaE emits only β-rays, a particularly suitable substance for the investigation of the con β-ray spectrum. This can be carried out either by experiments magnetic deflexion of the rays or by absorption measurements found that the energy content of the β-particles ejected by th of RaE varies between $1{\cdot}23 \times 10^6$ e.V. and 2×10^5 e.V., so th electrons that leave the nucleus of RaE differ in their energy va more than 1×10^6 e.V. By the measurement of the developm heat by the whole of the β-radiation from RaE it has been pos show that these energy differences do not arise from the occurr say secondary processes connected with the passage through the shells of the β-particles coming from the nucleus. This developm heat corresponded to $3{\cdot}37 \times 10^5$ e.V. per particle, and was equa mean energy of the continuous β-spectrum (cf. Table 27). Thus th ference of nuclear β-rays into secondary radiation does not take p the outer shell of the RaE atom, and the various RaE nuclei emit β-pa of different energy values. If the half-value period of freshly dep RaE be determined and compared with that for an older prepa most of which has already decayed, the two values of the peri found to be accurately identical, and the same statement holds case of the succeeding disintegration product RaF. From this it that the energy content of all the RaE atoms must be the sam likewise in the case of all the atoms of RaF. This is an unex result, since the various RaE atoms disintegrate into RaF emission of different amounts of β-ray energy.

In order to resolve this contradiction it is assumed that taneously with the emission of a β-particle, every RaE nucle emits a second very light particle that does not ionize. The en this 'neutrino', together with that of the electron (β-ray), is assu be equal to the difference in energy content between the original and that of the succeeding product of disintegration. Thus the the energies of the electron and the neutrino is the true energ t can be obtained from the upper limit of the β-spectrum; st electrons the energy of the neutrino is zero. According ·sis, the emission of β-radiation is not a unitary elementary ie emission of a light quantum, but a dual process con-imultaneous emission of an electron and a neutrino with total energy.

corresponding to the upper limit of the continuous several radio-elements is shown in Table 27, which also

TABLE 27

ıuous β-Ray Spectrum of several Radio-elements

T	*Average energy (in 10^5 e.V.)*	*Energy of the upper limit (in 10^5 e.V.)*
1·14 min.	8·2	23·2
26·8 ,,	2·3	6·5
19·7 ,,	7·4	31·5
5·0 days	3·4	12·3
6·13 hours	5·6	22·5
10·6 ,,	0·89	3·6
60·5 min.	8·0	22·0
3·1 ,,	5·8	18·0

lues of the average energy of the β-spectrum in each ılf-value periods of the radio-elements concerned.

s within the Disintegration Series

le relation between the disintegration constants of the ınd the ranges of the α-particles emitted. If, as in :he logarithm of the range as abscissa and the logarithm ıtion constant as ordinate, we obtain for each of the ıtion series a separate straight line. The relation fails es, as in those of RaC′ or AcX. However, the formula† basis of wave mechanics can be applied with some success ıamed cases. In addition to the quantities mentioned, involves the atomic number and the nuclear radius.

ion to that which holds for α-rays is also obtained for : the logarithm of the disintegration constant against the energy of the upper limit of the continuous β-ray 8). It will be seen that the points fall on two distinct anation of this, the view has been advanced that ish between those radio-elements whose disintegration with the same angular momentum as the disintegrating e for which this is not the case. The upper graph in

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† See footnote on p. 146.

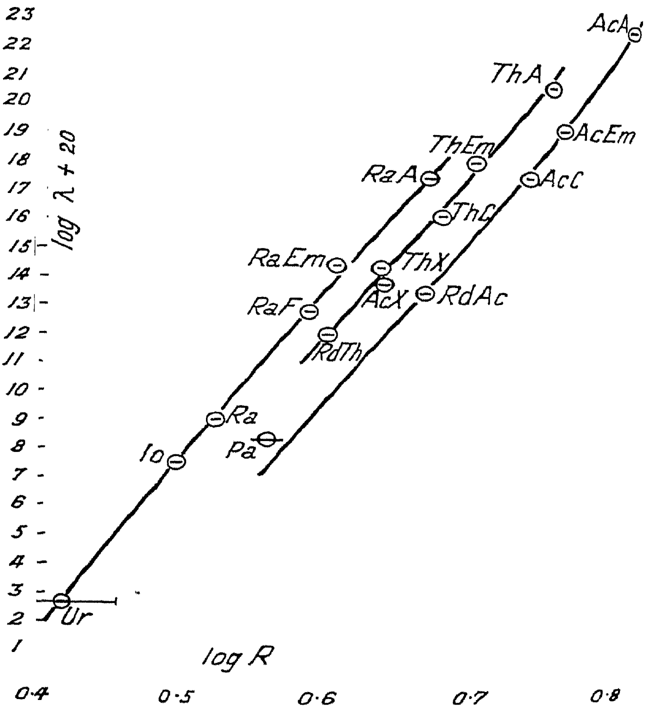

FIG. 37. Relation between the Range and the Disintegration Constant for α-Rayers.

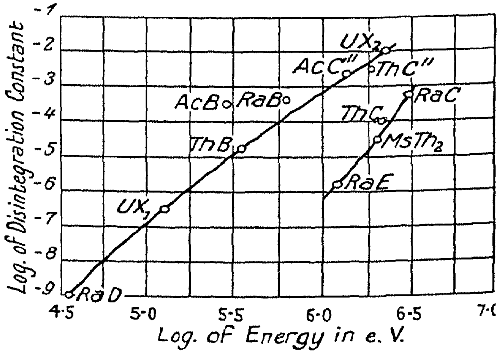

FIG. 38. Relation between the Energy of Disintegration and the Disintegration Constant for β-Rayers.

es the results for radio-elements whose nuclear angular
es not differ from that of the nucleus resulting from the
ation, whereas the lower graph refers to radio-elements
ray disintegration is accompanied by an alteration of one
gular momentum. In general, the probability of dis-
eases when there is no change in the angular momentum
tion.

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X

THE TRANSMUTATION OF THE ELEMENTS

THE elements owe their great stability to the protection affor the atomic nucleus by the potential barrier arising from the p electric field surrounding it. Charged particles, rich in energy, a to break through this barrier and effect a transmutation of the nucleus, but the harvest is in general a very modest one. As a particle which succeeds in penetrating the barrier is taken over nucleus, and in many cases this process leads to the ejection of a p another heavy particle. The outcome of all this is the formation ei stable nucleus or of a radioactive unstable nucleus, in which latt we are presented with an instance of radioactivity produced by a means. Let us first discuss the various types of nuclear tran tion without regard to whether or not the resulting nucleus is

The following *types of nuclear transmutation* are known:

(a) ${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\alpha = {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$
(b) ${}^{9}_{4}\mathrm{Be} + {}^{4}_{2}\alpha = {}^{12}_{6}\mathrm{C} + {}^{1}_{0}n$
(c) ${}^{9}_{4}\mathrm{Be} + {}^{1}_{1}\mathrm{H} = {}^{6}_{3}\mathrm{Li} + {}^{4}_{2}\mathrm{He}$
(d) ${}^{9}_{4}\mathrm{Be} + {}^{1}_{1}\mathrm{H} = {}^{8}_{4}\mathrm{Be} + {}^{2}_{1}\mathrm{D}$
(e) ${}^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} = {}^{8}_{4}\mathrm{Be}\,(+\gamma)$
(f) ${}^{12}_{6}\mathrm{C} + {}^{2}_{1}\mathrm{D} = {}^{13}_{7}\mathrm{N} + {}^{1}_{0}n$
(g) ${}^{23}_{11}\mathrm{Na} + {}^{2}_{1}\mathrm{D} = {}^{24}_{11}\mathrm{Na} + {}^{1}_{1}\mathrm{H}$
(h) ${}^{27}_{13}\mathrm{Al} + {}^{2}_{1}\mathrm{D} = {}^{25}_{12}\mathrm{Mg} + {}^{4}_{2}\mathrm{He}$
(i) ${}^{27}_{13}\mathrm{Al} + {}^{1}_{0}n = {}^{24}_{11}\mathrm{Na} + {}^{4}_{2}\mathrm{He}$
(j) ${}^{27}_{13}\mathrm{Al} + {}^{1}_{0}n = {}^{27}_{12}\mathrm{Mg} + {}^{1}_{1}$
(k) ${}^{27}_{13}\mathrm{Al} + {}^{1}_{0}n = {}^{28}_{13}\mathrm{Al}\,(+\gamma$
(l) ${}^{9}_{4}\mathrm{Be} + \gamma = {}^{8}_{4}\mathrm{Be} + {}^{1}_{0}$
(m) ${}^{7}_{3}\mathrm{Li} + {}^{2}_{1}\mathrm{D} = 2\,{}^{4}_{2}\mathrm{He} + {}^{1}_{0}$
(n) ${}^{11}_{5}\mathrm{B} + {}^{1}_{1}\mathrm{H} = 3\,{}^{4}_{2}\mathrm{He}$
(o) ${}^{10}_{5}\mathrm{B} + {}^{2}_{1}\mathrm{D} = 3\,{}^{4}_{2}\mathrm{He}$
(p) ${}^{44}_{20}\mathrm{Ca} + {}^{1}_{1}\mathrm{H} = {}^{44}_{21}\mathrm{Sc} + {}^{1}_{0}$
(q) ${}^{63}_{29}\mathrm{Cu} + {}^{1}_{0}n = {}^{62}_{29}\mathrm{Cu} + 2$

The possibility of a transmutation of the nucleus as a result of bo ment by particles rich in energy was first established in the case nated (a) above [1].

1. Nuclear Disruption caused by α-Rays

Magnesium bombarded by the α-rays from ThC′ emits three gr protons [2] having the ranges 31, 40·5, and 52 cm. All three gr protons are emitted in the capture of α-particles by the most ab isotope of magnesium, ^{24}Mg, and ^{27}Al is produced. The di between the mass defect of ^{24}Mg *plus* the mass and energy of particle and the mass defect of ^{27}Al *plus* the mass and energ proton emitted gives the amount of energy absorbed in the tra tion. The protons of range 52 cm. are emitted when the result nucleus is in the ground state, whereas for the other two ra resulting ^{27}Al nucleus is in an excited state. The corresponding a of energy in the latter cases which remain for the time being in the difference in energy of protons of range 52 cm. and one hand, and of 52 cm. and 31 cm. on the other.

the yield of disrupted atoms increases with the energy g particle, but this is by no means always the case. ruption of aluminium nuclei it is found that there are lues (resonance levels) of the incident α-particles which ective [3, 4]. In the bombardment of aluminium with ge 3·9 cm. protons of range up to 66 cm. are emitted. e α-radiation is reduced to 3·7 cm. by the introduction layer, say by an atmosphere of carbon dioxide, the ns emitted by the aluminium nuclei shows a marked further reducing the range to 3·45 cm. the emission ge number of protons is again observed, but now they ge up to 61 cm. Two additional resonance positions found for ranges of the incident α-particles of values respectively. A closer investigation showed that the n each case consist of two homogeneous groups, one of smaller energy, as can be seen from Table 28 [3]. A nergy is emitted when the captured α-particle takes up owest energy level in the nucleus, whereas the proton naller energy value when the α-particle takes up a n in a higher energy level. The difference in energy form of γ-rays when the α-particle passes over, in the to the lowest energy level of the aluminium nucleus.

TABLE 28

roduced by the α-Bombardment of Aluminium

Effective α-particle		*Range of protons ejected (in cm.)*
in cm.)	*Energy (in volts)*	
9	$5{\cdot}25 \times 10^6$	66 and 34
45	$4{\cdot}86 \times 10^6$	61 „ 30·5
1	$4{\cdot}49 \times 10^6$	55 „ 26·5
7	$4{\cdot}0 \times 10^6$	49 „ 22

n described is only detected when thin aluminium ne retardation of the α-particles takes place in a thick n, all eight groups of protons appear simultaneously. henomenon, according to which the yield of disrupted large for definite energy values of the disrupting eable only with relatively slow α-particles, and this hat in the following way. α-particles rich in energy nt the potential barrier, as in the case of α-particles n volts when they are incident on beryllium nuclei. on the other hand, being less energetic, are forced

to find their way through the potential barrier, and they can c
this to any appreciable extent when resonance levels exist. For
lium there are such levels at 2·5 and 1·4 million volts respectiv
that α-particles with these amounts of energy are able to traver
barrier with relative ease.

2. Nuclear Disruption caused by Protons and by Deuteron

The behaviour of lithium and of boron has been investigated
thoroughly with respect to positive rays of hydrogen, i.e. pro

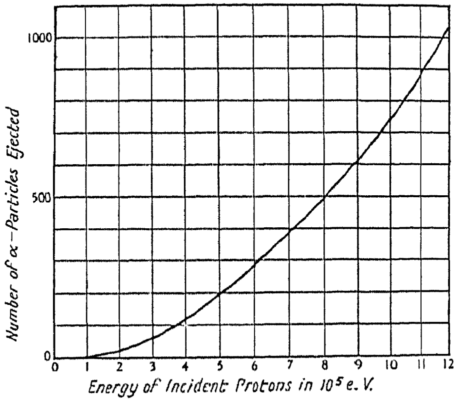

Fig. 39. Relation between the Number of α-Particles ejected from Lithium and the Energy of the Incident Protons.

different energy [5]. Disruption of lithium under emission of
has been detected even for a value of the incident energy of
but with increasing energy of the H-particles (cf. Fig. 39) the
of disruption rises rapidly. As the energy of the protons is raise
200 to 500 e.kV. the yield of disrupted atoms shows a ninefold i
and as the energy is raised to 1,200 e.kV. a further *c.* fivefold i
in the yield is noted; the value of the yield observed is here 5×10
highest yields are found in the bombardment of deuterium with
rays of heavy hydrogen; for incident rays of energy 1,000 e
yield of disrupted atoms amounts to one in a few thousands,
phenomenon of disruption is observed for a value of the energy
as 20 e.kV.

The phenomenon of resonance described on p. 109 has al
observed in a few cases of disruption by accelerated protons.
disruptive process $^{7}_{3}\mathrm{Li}+^{1}_{1}\mathrm{H} = ^{8}_{4}\mathrm{Be}\ (+\gamma)$, when very thin films of
are bombarded by protons, the yield increases very rapidly with
ing energy of the protons, attains a maximum at 0·45 e.kV., a
falls rapidly as the energy is still further increased.

y of the α-particles ejected when lithium is bombarded
ive a range of 8·4 cm., but particles are also present which
nges (0·5 to 1·7 cm.) and a similar frequency of occurrence.
articles arise from the process $^{6}_{3}\text{Li}+^{1}_{1}\text{H} = ^{4}_{2}\text{He}+^{3}_{2}\text{He}$,
rmer are due to the disruption of $^{7}_{3}\text{Li}$. In the disrup-
by deuterons, α-particles of range 13·2 cm. are observed,
up about ten times as strong with a continuous distribu-
etween 1 and 7·8 cm.; the former are the result of the
) $= 2\,^{4}_{2}\text{He}$, whereas the latter are due to the process
e$+^{1}_{0}n$. In addition, when the disruption takes place in
h the scheme $^{6}_{3}\text{Li}+^{2}_{1}\text{D} = ^{7}_{3}\text{Li}+^{1}_{1}\text{H}$, protons are also
a range of 30·5 cm. for deuterons of energy 500 e.kV.
f α-rays of range 8·4 cm. by lithium when it is bom-
nic rays takes place in accordance with the expression

$$^{7}_{3}\text{Li}+^{1}_{1}\text{H} = ^{8}_{4}\text{Be} = 2\,^{4}_{2}\text{He},\dagger$$

$$1{\cdot}0081 = 8{\cdot}0078+0{\cdot}0183 = 2\times 4{\cdot}0039+0{\cdot}0183.$$

t a loss of mass of 0·0183 takes place in the process.
gy‡ corresponding to a mass-difference of 0·0183 units
it has the value $17{\cdot}04\times 10^{6}$ e.V., so that we should
unt of energy to be released in the above process. Just
energy, more accurately $16{\cdot}97\times 10^{6}$ e.V., is found in
kinetic energy of the He-ions (α-particles) produced.
ses of atomic disruption are presented by the effect of
n heavy hydrogen [6] (deuterium); these are as follows:

$$+^{2}_{1}\text{D} = ^{3}_{1}\text{T} + ^{1}_{1}\text{H}, \qquad ^{2}_{1}\text{D}+^{2}_{1}\text{D} = ^{3}_{2}\text{He}+^{1}_{0}n.$$

t these processes lead to the formation of isotopes of
s 1 and 3, an isotope of helium of mass 3, and neutrons.

ruption caused by Neutrons

e elements can be transformed by bombardment with
the atomic number of the elements gets larger, the
so increases, and this progressively protects the nuclei
from the influence of incident charged particles.
elements of higher atomic number than say calcium
fected by bombardment with α-particles. Neutrons,

---

the $^{8}_{4}\text{Be}$ atoms so produced are in a highly excited state, but only
m disrupt into two α-particles; the remainder emit their excess
γ-rays of energy 17×10^{6} e.V. (cf. p. 123).

theory of relativity there exists between the energy content (E)
a system the simple relation $M = E/c^{2}$, where c represents the
e also Table 57, p. 294.)

on the other hand, having no charge, are able to reach ev heaviest nuclei and to become incorporated in them. In a consi of atomic transmutation under the action of neutrons it is ne to distinguish between three cases:

(*a*) The admission of the neutron into the nucleus is accom by the ejection of a proton, so that the atomic number is red one unit, whilst the nuclear mass remains unchanged.

(*b*) The admission of the neutron into the nucleus is accom by the ejection of an α-particle, so that the resulting element atomic number smaller by two units than the original element nuclear mass smaller by three units.

(*c*) The admission of the neutron is not accompanied by the of a nuclear constituent. The neutron is simply captured by the and the result is the formation of a higher isotope of the under consideration.

These three possibilities are well illustrated by consider behaviour of the element aluminium:

$$(a)\ {}^{27}_{13}\mathrm{Al}+{}^{1}_{0}n \longrightarrow {}^{27}_{12}\mathrm{Mg}+{}^{1}_{1}\mathrm{H}, \qquad (b)\ {}^{27}_{13}\mathrm{Al}+{}^{1}_{0}n \longrightarrow {}^{24}_{11}\mathrm{Na}+$$

$$(c)\ {}^{27}_{13}\mathrm{Al}+{}^{1}_{0}n \longrightarrow {}^{28}_{13}\mathrm{Al}.$$

To bring about the processes designated (*a*) and (*b*) it is neces use neutrons of high energy value, for the reaction (*a*) can on place when the sum of the masses of ${}^{27}_{13}\mathrm{Al}$ and ${}^{1}_{0}n$ *plus* the equ mass of the energy of the neutron exceeds the sum of the masses and the proton *plus* the equivalent mass of the kinetic energ proton. For this to be fulfilled it is necessary that the kinetic en the neutron shall have a value of several million electron vol third case (*c*) is different. This process is exothermic and can tak even in the entire absence of kinetic energy. Since slow ne are captured much more readily than fast ones, the process ceeds by preference under the influence of slow neutrons. been seen on p. 76 that these slow neutrons are produced by fast neutrons, such as those emitted by a radon-beryllium sou pass through water, paraffin wax, or other substances containing gen. The process (*c*) is sometimes designated 'hydrogen se and can be encouraged by surrounding the neutron source purpose with a layer of water or paraffin wax several centim thickness.

The process of nuclear disruption is usually studied by mak of a Wilson cloud chamber, or of the effect in an ionization cha a counter device of the ionizing particles produced during the dis process. In the case of the reaction

$${}^{10}_{5}\mathrm{B}+{}^{1}_{0}n = {}^{11}_{5}\mathrm{B} \qquad {}^{7}_{3}\mathrm{Li}+{}^{4}_{2}\mathrm{He}$$

ssible to establish the formation of helium by optical From the amount of helium determined in this work it that a beryllium-radon source containing 1 milli-curie at least $6{\cdot}7 \times 10^3$ neutrons per second [8].

es the products of transformation effected by neutrons ble atoms but unstable radioactive atoms. Such radio-es have been produced in large numbers by neutron

thod used for the production of artificial radioactive he bombardment with α-particles. This was soon re-method of neutron bombardment, which has a much application, and the technique of which is much ently, however, a very potent third method (the cyclo-s been introduced. In this method the elements are leuterons, and it is so effective that it is not unlikely e it will largely supersede all other methods. (See p. 114

ruption caused by γ-Rays

has been possible to bring about an alteration of the ction of γ-rays from the radium and thorium series [9]. which is a relatively weak structure, can be destroyed γ-rays, whereby an atom of heavy hydrogen is con-ght hydrogen atom and a neutron, in accordance ig expression:

$$^2_1\mathrm{D} + \gamma = {}^1_1\mathrm{H} + {}^1_0n.$$

n ThC″ are used, which possess an energy quantum of .V., particles $^1_1$H and ^1_0n are obtained, each of energy 'rom this it follows that the destruction of the deu-equires an amount of energy given by $2{\cdot}1 \times 10^6$ e.V. also can be disrupted by the γ-rays from radium icts, in accordance with the scheme:

$$^9_4\mathrm{Be} + \gamma = {}^8_4\mathrm{Be} + {}^1_0n.$$

n amount of energy of $1{\cdot}6 \times 10^6$ e.V. suffices for the ron from $^9_4$Be. It should be mentioned that the above iting the action of γ-rays on heavy hydrogen is re-een possible to observe the union of neutrons with companiment of γ-ray emission. The nuclear disrup-ry hard γ-rays produced artificially is discussed on

5. Production of Artificial Radioactivity by Neutrons

Many kinds of atoms arise from the action of neutrons on other types, and quite a number of them are unstable. These general β-rays when they disintegrate, and the resulting products are atoms of another element. In order to illustrate the processes integration of atoms rendered radioactive by artificial means w consider the case of the activation of aluminium discussed on In this process the following three isotopes of elements are pr from aluminium when it is bombarded by neutrons: $^{27}_{12}$Mg, $^{24}_{11}$N All three of these products are radioactive, and they disinteg accordance with the following schemes:

$$^{27}_{12}\mathrm{Mg} = {}^{27}_{13}\mathrm{Al} + \beta \quad (T = 12 \text{ min.}),$$
$$^{24}_{11}\mathrm{Na} = {}^{24}_{12}\mathrm{Mg} + \beta \quad (T = 15 \text{ hours}),$$
$$^{28}_{13}\mathrm{Al} = {}^{28}_{14}\mathrm{Si} + \beta \quad (T = 2{\cdot}3 \text{ min.}).$$

Of these three processes the first is the most interesting, in s it leads to the formation of the only stable isotope of aluminiu the element originally bombarded by neutrons. By means of ne it is possible in this case temporarily to suppress the existence stable isotope of aluminium, but this initial element is formed the half-value period of growth being 12 minutes. On the other in the other two cases of the transmutation of aluminium, isotopes of Mg and Si are the resulting end-products.

Experiment shows that the same mass-number (atomic mas associated with two atomic types of the same element, one being stable and the other active or unstable. Thus $^{53}_{24}$Cr is type of chromium. The union of a neutron with the most a isotope of chromium $^{52}_{24}$Cr does not result in the formation of active isotope, but of the stable isotope $^{53}_{24}$Cr, for the existence latter excludes that of a radioactive isotope $^{53}_{24}$Cr. Most of the ele of even atomic number have numerous isotopes, and the un neutrons with such elements leads in many cases of necessity to higher isotopes of the same element having a higher atomic The occurrence of such processes can be established by abs experiments (cf. p. 112). In all cases where absorption of neu observed and artificial radioactivity does not result from the it is possible to conclude that a stable isotope or an isotope life has been formed by the act of absorption. Moreover, such a is often associated with the emission of γ-rays in detectable a for the energy liberated by the addition of neutrons is emitted form.

ns are captured and this is accompanied by the emission
esult is an element of lower atomic number. The latter
ell as those in which protons are emitted, have only been
he lighter elements up to and including zinc, when
ed by radium-beryllium (or radon-beryllium) sources
. Under the action of such particles, the majority of the
und only to form a simple union with neutrons. By
ardment with deuterons and other particles of very large
een possible to observe the emission of material particles
re of neutrons even by the heavier elements.

ive isotopes produced artificially by neutrons are shown
far as they are known, and their half-value periods
ed in the table. It begins with the element lithium,
nts with an atomic number less than 3 no activity
as a result of their bombardment with neutrons. The
f the elements bombarded by neutrons are printed in

ion of the table reveals that the observed periods lie
econds and a few years. Energy considerations render
at numerous undiscovered radioactive types of atoms
ay with a period of only a fraction of a second. On the
erous long-lived radioactive isotopes may be capable
ir periods of life being too short for them to be still
they have been formed at a time when the substances
tion were subjected to bombardment by neutrons in
the universe, and too long for them to be produced in
tity by the action of radiation in the laboratory during
s or weeks. The element $^{40}_{19}K$, which is responsible for
activity of potassium, has a period of life sufficiently
at it has not yet completely disintegrated in terrestrial
ourse of geological time [10]. Here we have a radio-
very long life which was produced in pre-terrestrial
f the process

$$^{39}_{19}K + ^{1}_{0}n = ^{40}_{19}K,$$

analogous reaction such as

$$^{40}_{20}Ca + ^{1}_{0}n = ^{40}_{19}K + ^{1}_{1}H.$$

e same radioactive isotope can be produced in different
learly revealed in Table 29. Thus the isotope $^{28}_{13}Al$ can
r from Al, Si, or P, and the isotope $^{52}_{23}V$ from V, Cr, or
f the attachment of neutrons to the nuclei of thorium
7, 13] calls for special mention. In the first case a new

TABLE 29. (Cf. Table 56, p. 292).

Radioactive Isotopes produced by Neutron Bombardment of the Elements [11]

Element bombarded	*Mass-numbers of stable isotopes of element bombarded*	*Resulting radioactive isotope*	*Half-value p resulting i*
3 Li	6, *7*	${}^{8}_{3}\mathrm{Li}$	0·8 s.
4 Be	8, *9*, 10	${}^{6}_{2}\mathrm{He}$	1 s.
8 O	*16*, 17, 18	${}^{16}_{7}\mathrm{N}$	9 s.
9 F	*19*	${}^{16}_{7}\mathrm{N}$; ${}^{19}_{8}\mathrm{O}$; ${}^{20}_{9}\mathrm{F}$	9 s.; 31 s.; 8 s.
10 Ne	*20*, 21, 22		
11 Na	*23*	${}^{23}_{10}\mathrm{Ne}$; ${}^{24}_{11}\mathrm{Na}$	33 s.; 15 h.
12 Mg	*24*, 25, 26	${}^{23}_{10}\mathrm{Ne}$; ${}^{27}_{12}\mathrm{Mg}$; ${}^{24}_{11}\mathrm{Na}$	33 s.; 12 m.;
13 Al	*27*	${}^{28}_{13}\mathrm{Al}$; ${}^{27}_{12}\mathrm{Mg}$; ${}^{24}_{11}\mathrm{Na}$	2·3 m.; 12 m.;
14 Si	*28*, 29, 30	${}^{28}_{13}\mathrm{Al}$; ${}^{31}_{14}\mathrm{Si}$	2·3 m.; 2·5 h.
15 P	*31*	${}^{28}_{13}\mathrm{Al}$; ${}^{31}_{14}\mathrm{Si}$; ${}^{32}_{15}\mathrm{P}$	2·3 m.; 2·5 h.;
16 S	*32*, 33, 34	${}^{32}_{15}\mathrm{P}$	14·5 d.
17 Cl	*35*, *37*	${}^{38}_{17}\mathrm{Cl}$† ; ${}^{32}_{15}\mathrm{P}$† ; ${}^{35}_{16}\mathrm{S}$	38 m.; 14·5 d.;
18 A	36, 38, *40*	${}^{41}_{18}\mathrm{A}$	110 m.
19 K	*39*, 40, 41	${}^{42}_{19}\mathrm{K}$; ${}^{41}_{18}\mathrm{A}$	12·5 h.; 110 m.
20 Ca	*40*, 42, 43, 44	${}^{45}_{20}\mathrm{Ca}$† ; ${}^{42}_{19}\mathrm{K}$	2·3 h.; 12·5 h.
21 Sc	*45*	${}^{42}_{19}\mathrm{K}$; ${}^{46}_{21}\mathrm{Sc}$	12·5 h.; 90 d.
22 Ti	46, 47, *48*, 49, 50	${}^{51}_{22}\mathrm{Ti}$; ${}^{45}_{20}\mathrm{Ca}$	3 m.; 2·3 h.
23 V	*51*	${}^{52}_{23}\mathrm{V}$	3·8 m.
24 Cr	50, *52*, 53, 54	${}^{52}_{23}\mathrm{V}$	3·8 m.
25 Mn	*55*	${}^{52}_{23}\mathrm{V}$; ${}^{56}_{25}\mathrm{Mn}$	3·8 m.; 2·5 h.
26 Fe	54, *56*, 57	${}^{56}_{25}\mathrm{Mn}$	2·5 h.
27 Co	57, *59*	${}^{60}_{27}\mathrm{Co}$; ${}^{56}_{25}\mathrm{Mn}$; ${}^{59}_{26}\mathrm{Fe}$	c. 1 y.; 2·5 h.;
28 Ni	*58*, *60*, 61, 62, 64	${}^{58}_{27}\mathrm{Co}$; ${}^{60}_{27}\mathrm{Co}$; ${}^{63}_{28}\mathrm{Ni}$	11 m.; c. 1 y.;
29 Cu	*63*, *65*	${}^{66}_{29}\mathrm{Cu}$; ${}^{64}_{29}\mathrm{Cu}$† ; ${}^{63}_{28}\mathrm{Ni}$	5 m.; 12·5 h.;
30 Zn	*64*, *66*, 67, *68*, 70	${}^{66}_{29}\mathrm{Cu}$; ${}^{64}_{29}\mathrm{Cu}$†	5 m.; 12·5 h.
31 Ga	*69*, *71*	${}^{70}_{31}\mathrm{Ga}$; ${}^{72}_{31}\mathrm{Ga}$	20 m.; 23 h.
32 Ge	*70*, *72*, 73, *74*, 76	${}^{75}_{32}\mathrm{Ge}$† ; ${}^{?}_{32}\mathrm{Ge}$†	20 h.; 30 m.
33 As	*75*	${}^{76}_{33}\mathrm{As}$	26 h.
34 Se	74, 76, 77, *78*, *80*, 82	${}^{?}_{34}\mathrm{Se}$	1 h.
35 Br	*79*, *81*	${}^{80}_{35}\mathrm{Br}$; ${}^{80}_{35}\mathrm{Br}$; ${}^{82}_{35}\mathrm{Br}$	18 m.; 4·5 h.;
36 Kr	78, 80, 82, 83, *84*, 86	? ; ? ; ?	18 h.; 4·5 h.;
37 Rb	*85*, *87*	${}^{86}_{37}\mathrm{Rb}$† ; ${}^{88}_{37}\mathrm{Rb}$†	18 m.; 18 d.
38 Sr	84, 86, 87, *88*	${}^{89}_{38}\mathrm{Sr}$	3 h. and 55 d.
39 Y	*89*	${}^{90}_{39}\mathrm{Y}$	70 h.
40 Zr	*90*, 91, *92*, *94*, 96	${}^{97}_{40}\mathrm{Zr}$	44 h.
41 Nb	*93*		
42 Mo	92, 94, *95*, *96*, 97, *98*, 100	${}^{?}_{42}\mathrm{Mo}$; ${}^{?}_{42}\mathrm{Mo}$; ${}^{?}_{42}\mathrm{Mo}$	2·5 m.; 17 m.;
44 Ru	96, 99, 100, *101*, *102*, 104	${}^{?}_{44}\mathrm{Ru}$; ${}^{?}_{44}\mathrm{Ru}$; ${}^{?}_{44}\mathrm{Ru}$	100 s.; 11 h.;
45 Rh	101, *103*	${}^{?}_{45}\mathrm{Rh}$; ${}^{?}_{45}\mathrm{Rh}$	44 s.; 3·9 m.
46 Pd	102, 104, *105*, *106*, *108*, 110	${}^{?}_{46}\mathrm{Pd}$; ${}^{?}_{46}\mathrm{Pd}$; ${}^{?}_{46}\mathrm{Pd}$	3 m.; 12 h.;
47 Ag	*107*, *109*	${}^{106}_{47}\mathrm{Ag}$; ${}^{110}_{47}\mathrm{Ag}$† ; ${}^{108}_{47}\mathrm{Ag}$†	24·5 m. and 2·3 m.
48 Cd	106, 108, *110*, *111*, *112*, *113*, 116	${}^{?}_{48}\mathrm{Cd}$; ${}^{?}_{48}\mathrm{Cd}$; ${}^{?}_{48}\mathrm{Cd}$; ${}^{106}_{47}\mathrm{Ag}$; ${}^{108}_{47}\mathrm{Ag}$; ${}^{110}_{47}\mathrm{Ag}$; ${}^{111}_{47}\mathrm{Ag}$; ${}^{112}_{47}\mathrm{Ag}$	33 m.; 4·3 h.; and 8·2 d.; 7·5 d.; 3·2 h.
49 In	113, *115*	${}^{116}_{49}\mathrm{In}$; ${}^{116}_{49}\mathrm{In}$; ${}^{112}_{47}\mathrm{Ag}$	13 s.; 54 m.;

TABLE 29 (*cont.*)

nbers of stable *s of element* *nbarded*	*Resulting radioactive isotope*	*Half-value period of resulting isotope*
15, 116, 117, , *120*, 122, 124	$^{?}_{50}Sn$; $^{?}_{50}Sn$	8 m.; 18 m.
	$^{120}_{51}Sb$; $^{122}_{51}Sb$; $^{124}_{51}Sb$	16 m.; 2·5 d.; 60 d.
24, 125, *126*,	$^{?}_{52}Te$	1·1 h.
	$^{128}_{53}I$	25 m.
	$^{134}_{55}Cs$	1·5 h.
34, 135, 136,	— ; $^{139}_{56}Ba†$	2·5 m.; 80 m.
	$^{140}_{57}La$	1·3 d.
	$^{142}_{59}Pr$; $^{142}_{59}Pr$	3 m.; 19 h.
44, 145, 146	$^{147}_{60}Nd†$	2 h.
18, 149, 150	$^{151}_{62}Sm$; $^{153}_{62}Sm$	21 m.; 2 d.
	$^{154}_{63}Eu†$	9·3 h.
57, *158*, 160		
	$^{160}_{65}Tb$	3·9 h.
63, *164*	$^{165}_{66}Dy$	2·5 h.
	$^{166}_{67}Ho$	30 h.
8, 170	$^{171}_{68}Er†$; $^{169}_{68}Er†$	7 m.; 12 h.
	$^{170}_{69}Tm$	120 d.
3, *174*, 176	$^{175}_{70}Yb†$	2·1 h.
	$^{176}_{71}Lu$; $^{177}_{71}Lu†$	4 h.; 8 d.
8, 179, *180*	$^{181}_{72}Hf$	55 d.
	$^{180}_{73}Ta‡$; $^{182}_{73}Ta$	8 h.; 97 d.
4, *186*	?	1 d.
	$^{?}_{75}Re$; $^{?}_{75}Re$; $^{?}_{75}Re$	20 m.; 18 h.; 85 h.
8, 189, *190*	$^{?}_{76}Os$	40 h.
	$^{192}_{77}Ir$; $^{194}_{77}Ir$; $^{?}_{77}Ir$; $^{?}_{77}Ir$	2 m.; 1·5 m. and 19 h.; 28 m.; 8·5 h.
5, *196*, 198	$^{197}_{78}Pt$; $^{199}_{78}Pt$	18 h. and 3·3 d.; 50 m.
	$^{198}_{79}Au$	2·7 d.
8, 199, *200*, 03, 204	$^{205}_{80}Hg$	41 h.
	$^{204}_{81}Tl†$; $^{206}_{81}Tl†$	5 m.; 97 m.
, *208*	$^{209}_{82}Pb$	3 h.
	$^{229}_{88}Ra$; $^{233}_{91}Pa$; $^{229}_{89}Ac$; $^{233}_{90}Th$; $^{229}_{89}Ac$	1 m.; 2·5 m.; 12 m.; 28 m.; 3·5 h.
	$^{239}_{92}U$; $^{237}_{92}U$	23 m.; 10 s. and 40 s. (see below)

nty; thus the resulting isotope may have another mass; or in
duced instead of ^{38}Cl, and so on.
fter the capture of 1 fast neutron.

rmation series is produced (see Table 29), and hence , Ac, Ra, and so on, whereas in the case of uranium, number higher than that of uranium 92 are formed, some of which are higher homologues of rhenium, osmium, iridi platinum. The following are the reactions observed:

$$(a)\quad {}_{92}\mathrm{U}+{}_{0}n\left(\begin{matrix}\text{slow}\\ \text{or}\\ \text{fast}\end{matrix}\right.\longrightarrow({}_{92}\mathrm{U}+n)\xrightarrow[(10\,\text{s.})]{\beta}{}_{93}\text{Eka-Re}\xrightarrow[(2{\cdot}2\,\text{m.})]{\beta}{}_{94}]$$

$$\xrightarrow[(59\,\text{m.})]{\beta}{}_{95}\text{Eka-Ir}\xrightarrow[(66\,\text{h.})]{\beta}{}_{96}\text{Eka-Pt}\xrightarrow[(2{\cdot}5\,\text{h.})]{\beta}$$

$$(b)\quad {}_{92}\mathrm{U}+{}_{0}n\,(\text{fast})\longrightarrow({}_{92}\mathrm{U}+n)\xrightarrow[(40\,\text{s.})]{\beta}{}_{93}\text{Eka-Re}\xrightarrow[(16\,\text{m.})]{\beta}{}_{94}]$$

$$(5{\cdot}7\,\text{h.})$$

$$(c)\quad {}_{92}\mathrm{U}+{}_{0}n\,(\text{slow})\longrightarrow({}_{92}\mathrm{U}+n)\xrightarrow[(23\,\text{m.})]{\beta}{}_{93}\text{Eka-Re}(?$$

(The half-value periods o the relevant disintegrations are g brackets beneath the arrows.)

Whereas it is necessary to use neutrons of high energy in produce both $^{27}_{12}\mathrm{Mg}$ and $^{24}_{11}\mathrm{Na}$ from $^{27}_{13}\mathrm{Al}$, this is not the cas production of radio-aluminium $^{28}_{13}\mathrm{Al}$, for the last-named proce rise to a greater yield with slow neutrons than with fast n This statement holds quite generally for the production o isotopes of the element bombarded, in contrast to the produ isotopes of other elements. In the former process all that hap the incorporation of a neutron into the nucleus without ejecti α-particle or a proton, and since such a process is an exother it does not involve the addition of energy in the form of kineti of the neutrons. But when radio-elements are produced with t of an α- or an H-particle, this is only possible by the additio amount of energy represented by several millions of volts in t of kinetic energy of the bombarding neutrons. For this reason preparation of higher isotopes by bombardment with neutro velocity of the neutrons is very greatly reduced by the intro of paraffin wax, water, or similar substances (cf. p. 76). The n gradually give up their energy by repeated collision with the h nuclei, and the probability of capture of these quite slow neut thus in many cases markedly greater than that of fast neutrons as are emitted by a beryllium-radium source. In this way, for ex it is possible to attain a 40-fold yield in the preparation of radio and even a 100-fold yield in the preparation of radio-dyspros

From amongst the various methods that lead to the produc artificial radioactivity, that of the bombardment by neutrons is

the best yield (see, however, p. 113). All the neutrons
aptured by nuclei, and by suitably devised arrangements
ensure that practically all of them are absorbed in the
transformation is desired. On the other hand, only a
f incident α-particles or accelerated protons (cf. p. 112)
cleus, whereas the large majority of them lose their
ction with the shell of the atom and can be disregarded
of nuclear constitution. The transmutation process
lerated deuterons results in individual cases in a much
here the yield can amount to as much as 1 transmuted
w thousand deuterons.

of Artificial Radioactivity by α-Rays [14]

nents situated between boron and calcium have been
the influence of α-rays. After the capture of the α-
tomic nucleus, this emits either a neutron or a proton
e isotope of a new element is formed. The bombard-
-particles leads either to the formation of a radioactive
e with the equation

$$^{24}_{12}\mathrm{Mg} + {}^{4}_{2}\alpha = {}^{27}_{14}\mathrm{Si} + {}^{1}_{0}n,$$

tive isotope $^{28}_{13}\mathrm{Al}$ according to the equation

$$^{25}_{12}\mathrm{Mg} + {}^{4}_{2}\alpha = {}^{28}_{13}\mathrm{Al} + {}^{1}_{1}\mathrm{H}.$$

f another element may of course also result from such
when Al is bombarded by α-rays the resulting product
e radioactive isotope $^{30}_{15}\mathrm{P}$ with emission of a neutron,
tope $^{30}_{14}\mathrm{Si}$ in agreement with the equation

$$^{27}_{13}\mathrm{Al} + {}^{4}_{2}\alpha = {}^{30}_{14}\mathrm{Si} + {}^{1}_{1}\mathrm{H}.$$

ass-number cannot be associated both with an active
e isotope of the same element, a stable isotope must
st-named process, the isotope $^{30}_{14}\mathrm{Si}$ being stable.

ls rich in the rare earths contain appreciable amounts
orium, as well as of light elements such as beryllium
d in the course of geological time some of the rare
ntained in these minerals have undergone a slight
olinium, which absorbs slow neutrons very strongly,
d in this connexion.

ive isotopes resulting from bombardment by neutrons
e with emission of β-particles whose half-value thick-
0·04 and 0·25 gm. cm.^{2} aluminium, the radioactive
by bombardment with α-particles show a different
siderable proportion of these isotopes disintegrate

with emission of positrons. By incorporating the two charge α-particle, the resulting isotope has too many protons in pro to its neutron content, so that it possesses too many positive and gets rid of these by emitting positrons. Table 30 contains radioactive isotopes produced by bombardment with α-partic in the table it is also stated whether the radioactive isotope positron or an electron.

TABLE 30

Radioactive Isotopes produced by Bombardment with α-Parti

Isotope bombarded	*Particle emitted*	*Isotope produced*	*Half-value period*
$^{10}_{5}$B	*n*	$^{13}_{7}$N (+)	11 min.
$^{14}_{7}$N	*n*	$^{17}_{9}$F (+)	1·2 min.
$^{19}_{9}$F	*n*		3 years
$^{23}_{11}$Na	*n*	$^{26}_{13}$Al (+)	7 sec.
$^{24}_{12}$Mg	*n*	$^{27}_{14}$Si (+)	6 min.
$^{25}_{12}$Mg	*p*	$^{28}_{13}$Al ( )	2·3 min.
$^{26}_{12}$Mg	*p*	$^{29}_{13}$Al ( )	11 min.
$^{27}_{13}$Al	*n*	$^{30}_{15}$P (+)	3 min.
$^{29}_{14}$Si	*p*	$^{32}_{15}$P ( )	15 days
$^{31}_{15}$P	*n*	$^{34}_{17}$Cl ( )	33 min.
$^{39}_{19}$K		$^{42}_{21}$Sc (−)	3 hours
$^{40}_{20}$Ca		$^{43}_{21}$Sc ( )	4·0 hours

n = neutron; *p* = proton; (+) indicates that the isotope produced dis with emission of positrons, and (−) that it disintegrates with emission of ele

All the known stable as well as radioactive isotopes in the between hydrogen and krypton are incorporated in Fig. atomic number is plotted as abscissa, whereas the ordinates re the difference between the mass-number and twice the atomic The isotopes indicated by circles in heavy line are stable, and concentration of the relevant isotope in the mixed element is than 5 per cent. it is represented by a large circle, otherwise by one. The circles contain the mass-number, and also the half period when the isotope is unstable. Circles in thin line represen isotopes; if the upper half of the circle is in broken line, ○, the isotope disintegrates with emission of β-rays, but if the lower the circle is in broken line, ○, positrons are emitted during disi tion. Active isotopes that are lighter than the stable types disin with emission of positrons (see Table 56); here the structure conta many protons in proportion to neutrons, and diminishes its ex charge number by ejection of a positive charge. On the other han isotopes that disintegrate with emission of β-rays contain too neutrons for them to be stable, and alter their neutron:proton by ejecting a negative electron, which corresponds to their tak

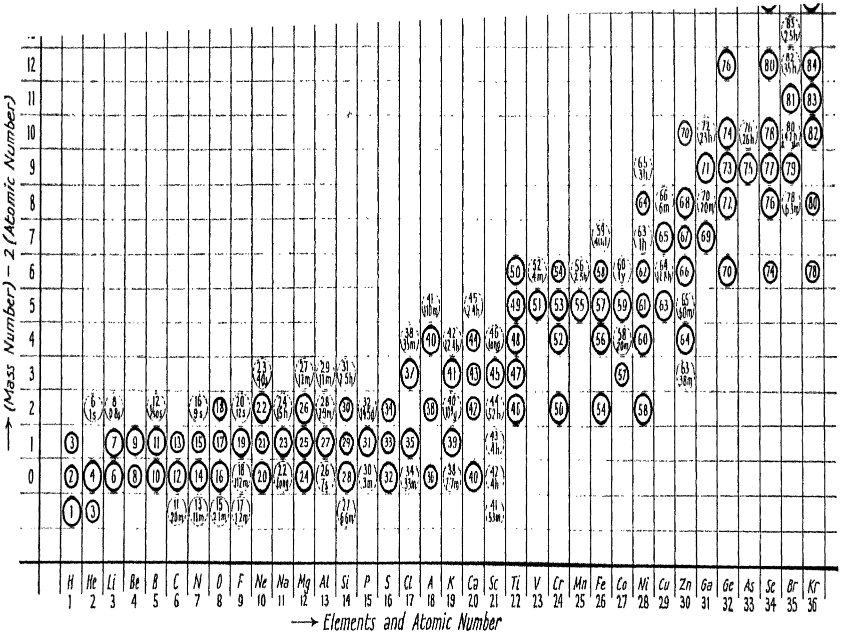

FIG. 40. Diagram incorporating most of the known Stable and Radioactive Isotopes from Hydrogen (1) to Krypton (36). (See Tables 29 and 56.)

a positive charge. When substances are bombarded by neutron ducts are always obtained which, if unstable, contain too many ne and hence disintegrate with emission of β-particles. Isotope disintegrate with emission of positrons have arisen as a re the nuclei taking up α-particles or other positively charged particles.

In the production of artificial radioactivity by means of α-par the yield is a very modest one [16]. For every 10^7 α-particles o energy value ($8{\cdot}3 \times 10^6$ e.V.) incident upon it, only 6 are effec the activation of aluminium, i.e. in the production of radio-phos ($^{30}_{15}P$), and the yield of radio-phosphorus produced falls rapi the range of the incident α-particles is diminished, as can be s Table 31.

TABLE 31

Dependence of Activation on the Energy of the Incident α-Parti

Energy of incident α-particles	*Yield*†
$8{\cdot}25 \times 10^6$ e.V.	$6{\cdot}4 \times 10$
7·61 ,,	4·7 ,,
6·66 ,,	1·1 ,,
5·49 ,,	0·13 ,,
4·81 ,,	0·02 ,,
4·20 ,,	0·00 ,,

† Yield = probability that an α-particle of energy E will at some form a radio-phosphorus atom.

As seen in the table, the yield in the production of radio-phos is very small; that of the production of other artificial radio-ele with the aid of α-rays is still smaller.

7. Production of Artificial Radioactivity by Deuterons γ-Rays

A number of artificial radio-elements have been generated und influence of accelerated deuterium ions in the region between bor aluminium [17]; representative cases are collected together in Ta Whereas some disintegrate with emission of positrons, others electrons.

When any substance is bombarded by deuterons, an activ observed which decays with a period of 2 minutes. It is to be as to the disintegration of $^{15}_{8}O$, which has been generated by the ac the deuterons on the atoms of the nitrogen $^{14}_{7}N$ in the air [18].

We have seen that neutrons are produced [9] when γ-ra

TABLE 32

adioactive Isotopes produced by Bombardment with Deuterons

Bombarded isotope	*Particles emitted*	*Isotope produced*	*Half-value period*
$^{10}_{5}\mathrm{B}$	n	$^{11}_{6}\mathrm{C}$ (+)	20 min.
$^{12}_{6}\mathrm{C}$	n	$^{13}_{7}\mathrm{N}$ (+)	10·5 min.
$^{14}_{7}\mathrm{N}$	n	$^{15}_{8}\mathrm{O}$ (+)	2·1 min.
$^{23}_{11}\mathrm{Na}$	p	$^{24}_{11}\mathrm{Na}$ (−)	15 hours
$^{24}_{12}\mathrm{Mg}$	α	$^{22}_{11}\mathrm{Na}$ (−)	3 yrs.
$^{27}_{13}\mathrm{Al}$	p	$^{28}_{13}\mathrm{Al}$ (−)	2·3 min.

d to impinge on beryllium or on deuterium. γ-rays are accordingly
call forth an artificial radioactivity in the presence of these
its [19]. In consequence of the relatively small energy of the
ns liberated, however, it is possible in this way to bring about
ssociation processes, by the formation of a radioactive isotope
ıer mass-number. In the most favourable case, when the total
tion is absorbed in beryllium, the yield can attain that which
be obtained by the effect of an equivalent amount of α-rays on
ım, i.e. by the α-rays emitted from the same quantity of radium.
ld be noted, however, that in the latter case the neutrons have
s up to 10^7 e.V., and they can accordingly also produce types of
other than higher isotopes of the bombarded elements, as in
duction by fast neutrons of $^6_2\mathrm{He}$ from $^9_4\mathrm{Be}$, by virtue of the
$^9_4\mathrm{Be}+{}^1_0n = {}^6_2\mathrm{He}+{}^4_2\mathrm{He}$.

ombarding a lithium target with protons of minimum energy
e.V., γ-rays of very great hardness ($17 \cdot 10^6$ e.V.) can be pro-
These rays are able to bring about nuclear photo-effects by the
of neutrons from the nuclei of various elements such as phos-
copper, and bromine, the resulting radioactive isotope having
number reduced by one unit [20].

lear from what has been said above that it is possible to produce
er of artificial radio-elements in a variety of ways. To take one
, the following methods have been successfully applied in the
tion of radio-aluminium $^{28}_{13}\mathrm{Al}$, which decays with a half-value
f 2·3 minutes, and emits β-rays whose half-value thickness in
um amounts to 0·16 gm. cm.^{2}:

$^{27}_{13}\mathrm{Al} + \quad = {}^{28}_{13}\mathrm{Al}$, $\qquad$ $^{28}_{14}\mathrm{Si} \quad {}_0n = {}^{28}_{13}\mathrm{Al} + {}^1_1\mathrm{H}$,

$^{31}_{15}\mathrm{P} + {}^1_0n = {}^{28}_{13}\mathrm{Al} + {}^4_2\mathrm{He}$, $\qquad$ $^{25}_{12}\mathrm{Mg} + {}^4_2\alpha = {}^{28}_{13}\mathrm{Al} + {}^1_1\mathrm{H}$,

$^{27}_{13}\mathrm{Al} + {}^2_1\mathrm{D} = {}^{28}_{13}\mathrm{Al} + {}^1_1\mathrm{H}$.

roduction of the silver isotope $^{106}_{47}\mathrm{Ag}$ can also be effected in
ways, one of which is the reaction

$$^{105}_{46}\mathrm{Pd}+{}^2_1\mathrm{D} = {}^{106}_{47}\mathrm{Ag}+{}^1_0n.$$

This isotope of silver is of interest, as it has two half-value pe 24·5 m. and 8·2 d., the former being associated with positron emi and the latter with the emission of β- and γ-rays, the number of per β-ray being about 35. Here we are confronted with the phenom of *nuclear isomerism* [21], the branching ratio in the present ins being about 20:1 in favour of the longer period. It seems like the capture of orbital electrons presents an alternative to po emission, and in the case of heavy radioactive nuclei the prob of such *K*-electron capture, accompanied by β- and relatively γ-ray emission, is theoretically about 1,000 times greater than the emission of positrons. The isotope of bromine $^{80}_{35}$Br also con radioactive isomers with half-value periods of 18 m. and 4·2 h. this case both isomers emit β-rays, together with γ-rays. The active isotope of potassium $^{40}_{19}$K, in addition to its normal β-disi tion into $^{40}_{20}$Ca, probably also emits positrons with formation and some of the argon in the earth's crust and in the atmospher have originated in this way.

8. Accurate Determination of Atomic Weights on the Bas Nuclear Reactions [22]

In the formulae for nuclear reactions such as

$$^{9}_{4}\mathrm{Be}+^{2}_{1}\mathrm{D}=^{10}_{4}\mathrm{Be}+^{1}_{1}\mathrm{H}+\delta$$

we are concerned not only with the masses of the atomic types ^{9}B ^{10}Be, and ^{1}H, but also with the mass-equivalent (δ) of the energy protons emitted. Moreover, a very small mass corresponds to a large value of the energy (1 e.V. = $1{\cdot}0741\times10^{-9}$ units of weight). In the example cited above the conversion of the value $\delta = 4{\cdot}749\times10^{6}$ e.V. into units of atomic weight yields the 0·0051, so that the measurement of the large amounts of energy occur here corresponds to a very exact determination of the mass thus possible, by the measurement of the energy of the rays in nuclear reactions, as well as by the combination of various equ of nuclear reactions, to arrive at atomic weights of very great acc Most of the values of the atomic weights given in Table 43, p. 1 to oxygen, have been determined in this way (see p. 180). The num values are all referred to ^{16}O = 16·0000.

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XI

APPLICATIONS OF THE THEORY OF DISINTEGRAT

1. The Fundamental Assumption

The theory of radioactive disintegration is based on the single as tion that the number of atoms of a radio-element disintegrating a instant is always proportional to the number of atoms of that ele present.

If we have 10^{11} atoms of a given radio-element and 1,000 of disintegrate in a given interval of time, then if we have 10^{10} ato the same radio-element, the number disintegrating in the same will be 100, and so on. The factor of proportionality, or the 'disin tion constant' (λ) is found to be a quantity which is entirely inde of all outside conditions such as temperature, pressure, etc., and characteristic of the disintegration process under consideration.

Only rarely does natural disintegration lead directly to a stab duct; in most cases the disintegration of an atom is followed by a series of successive transformations. The conditions that arise are very complicated, but the theory of transformation enables us to pret them quantitatively, and to calculate the number of atoms of intermediate product present at any time, provided that the disin tion constants are known. It also indicates means of evaluatin disintegration constants when these cannot be directly determin

In what follows we shall deal with the application of the theo transformation in a few typical cases of successive processes of integration.

2. Production of a Substance of Short Life from a Parent stance of Long Life. Separation and Decay of UX

If we investigate the behaviour of uranium nitrate or of any uranium salt, we find that it emits β-rays in addition to α-rays may recall that the radioactivity is a property of the uranium and that it is entirely independent of the state of chemical combin of the element. If we submit the uranium salt to a process of c lization or to processes of chemical separation, we find that strength of the α-radiation from the substance is unaltered, but the β-radiation has been influenced. It is possible, in fact, e.g. addition of an iron salt to the solution of the uranium compoun later precipitation of the iron by means of ammonium carbon separate completely the β-radiation from the uranium. But this vith the same intensity from the precipitated iron salt. From nay conclude that the β-radiation has its origin not in the but in a radioactive product separable from uranium, and uranium X.

radiation of the iron salt does not remain constant, but exponentially; viz. after the lapse of about 24 days it has unk to one-half of its original intensity, after 48 days to er, in 72 days to one-eighth, and so on.† One of the chief istics of exponential decay is that, strictly speaking, the disn is not completely finished until after an infinite period of since the quantity and hence also the radiation of UX sinks to ^{3} of its original value after an interval of about 10 × 24 days, that, for practical purposes, and provided it were initially trong, we can assume the preparation to have completely fter this time, i.e. the tenfold half-value period.‡ It is owing racteristic of exponential decay that we always consider the e period' (T) of a radio-element, or the time during which the amount initially available decays, instead of the absolute of the preparation. Although the latter quantity is always ly infinite, it is finite for practical purposes, but it depends ength of the preparation concerned and on the sensitiveness suring instruments, whereas the half-value period does not. om the half-value period, we also make use of a quantity roportional to it, viz. the 'period of average life' (τ). This defined here just as in insurance statistics. We multiply eriod by the average number of individuals that attain, but vive this period, and divide the sum of all these products by mber of individuals. It can readily be shown mathematically riod of average life (τ) so defined is equal to $\frac{1}{\lambda}$, the reciprocal tegration constant λ, whereas the half-value period

$$T = \frac{1}{\lambda}\log_e 2 = \frac{0{\cdot}69}{\lambda}.$$

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rocess is represented mathematically by the formula $N_t = N_0 e^{-\lambda t}$, where ber of atoms originally present, and N_t the number present after a time t; egration constant, and e the base of the natural logarithms. It is assumed sity of the measured radiation is always proportional to the number of grating per unit time.

active substance can be detected for a longer period when we use more uments towards the end of the measurement than at the beginning. The surement over which one and the same instrument can be used rarely 0; hence by means of such an instrument the active preparation will be ctable after a time of magnitude ten times the half-value period.

value period (T) is the time for which $N_t = \frac{N_0}{2}$; and since $N_T = N_0 e^{-\lambda T}$, we

Thus, in the case of UX, the disintegration constant $\lambda = 0{\cdot}0283$ da and $\tau = 35{\cdot}4$ days, from which $T = 24{\cdot}5$ days.

The variation of the activity of UX separated from uranium, as function of the time, is shown in curve B of Fig. 41, and this curve the same time shows the proportional decrease in the number of atoms, on which the activity depends.

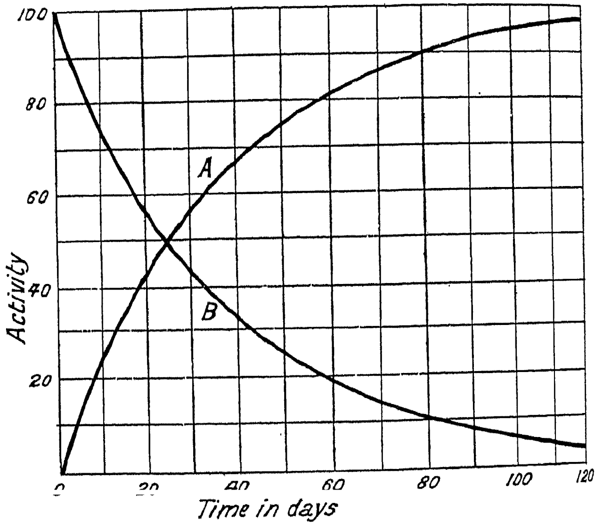

FIG. 41. Growth (A) and Decay (B) of Uranium X.

3. The Production of UX from Uranium

We shall now again turn our attention to the uranium prepa from which we have supposed the UX to have been removed, which therefore no longer emits β-rays. It is found graduall re-emit β-rays, and after the course of 24 (more exactly 24·5) it exhibits just one-half of the β-radiation that it had before separation of the UX. After 2×24 days it has reached $\frac{3}{4}$, after

must have $\frac{N_0}{2} = N_0 e^{-\lambda T}$. From this follows $T = \frac{1}{\lambda} \log_e 2$. The definition of the average life given above can be expressed mathematically in the form

$$\tau = \frac{\int\limits_0^\infty t\lambda N_0 e^{-\lambda t}\,dt}{N_0},$$

which is equal to $\frac{1}{\lambda}$. Since $\tau = \frac{1}{\lambda}$, we can also define the perio time within which the whole material would disintegrate, if the number of at integrating per unit time were to remain the same as initially: for

$$\frac{N_0}{N_0 \lambda} = \frac{1}{\lambda} = \tau.$$

he value last referred to, and so on. Moreover, this rise also
exponentially, and is graphically represented by the curve *A*

Just as the complete decay of the separated UX is to be
heoretically only after an infinitely long period of time, but
actical purposes already attained after 10×24 days, so also
tion of the UX-free uranium preparation will have practically
original strength after 10×24 days, although theoretically
require an infinite period of time. In Fig. 41 the decay of
tion of the separated UX and the growth of the β-radiation
ium preparation are represented on the same graph. From
at the sum of the two radiations, and hence the sum of the
er of UX atoms present, is constant at every instant, and
e initial value before the separation of the UX.

ctive Equilibrium

gration theory enables us to predict the behaviour described
ill be clear from the following example.

uppose that we have 10^{15} atoms of uranium ($= 4 \times 10^{-7}$ gm.).
alf-value period of uranium is approximately 10^{10} years, it
in 5 days, which we shall assume to be our unit of time, the
xceedingly small number of about 1,000 atoms will dis-
only the 10^{12}th part of all the available atoms. In the next
10^{12}th part of the now available atoms (10^{15}—1,000) will
; but the difference between this number and 10^{15} is so
small that, even if we require a very accurate calculation,
me them to be identical. Thus in each of the succeeding
days' duration we shall repeatedly find that 1,000 atoms
Not until after the lapse of many millions of years will
e amount of uranium have diminished appreciably, or the
ranium atoms disintegrating in each period of 5 days be
ifferent from 1,000, and this period of time is incomparably
the time involved in our investigation of the behaviour of
ed product UX.

0 disintegrated atoms have ceased to be uranium; by
disintegration they are now UX atoms, but only for a
of time. Since the period of average life of UX is only
out 15 per cent. or 150 of the 1,000 UX atoms will have
yed after 5 days; of the remaining 850, 15 per cent. or 127
the next 5 days, and this number is markedly different
accordance with the corresponding difference between
850 and 1,000, and so on. Thus in the course of 5 days
f disintegration exercises a very strong influence on the
X present, and hence also on the amount disintegrating.

The activity is proportional to the amount disintegrating at any ment, and thus our previous discussion makes it clear why the acti of uranium is practically constant, whereas that of the separated diminishes by about 15 per cent. even after a period of 5 days.

Let us now consider how much uranium X would be formed if it not separated from uranium, but left to itself. Whereas in each 5 1,000 fresh UX atoms are produced, independently of the num already present, the number of UX atoms disintegrating in the time will be greater the greater the number that have already formed. This behaviour necessarily leads to a state in which, for a interval of time, the number of UX atoms disintegrating will be e to the number freshly formed, so that the quantity of UX actu present no longer increases. This state is called 'radioactive brium'. A radio-element is in a state of radioactive equilibrium its disintegration product when the same number of atoms of daughter element disintegrate as are formed in the unit of time. Th important considerations will be quite clear from a study of Table

TABLE 33

Development of Radioactive Equilibrium

Number of time-intervals of 5 days	*Number of* UX *atoms produced in the interval by the decay of* U *atoms*	*Number of* UX *atoms available from the previous time-interval*	*Sum of the two numbers*	*Number of* UX *atoms decaying in the interval of time*	*Numb* UX *at remain the end time-*
1	1,000	..	1,000	150	[illegible]
2	1,000	850	1,850	277	[illegible]
3	1,000	1,573	2,573	386	[illegible]
4	1,000	2,187	3,187	478	[illegible]
5	1,000	2,709	3,709	556	[illegible]
6	1,000	3,153	4,153	623	[illegible]
7	1,000	3,530	4,530	680	[illegible]
8	1,000	3,850	4,850	728	[illegible]
9	1,000	4,122	5,122	768	[illegible]
10	1,000	4,354	5,354	803	[illegible]
..	....	....	....	...	...
..	....	....	....	...	....
..	....	....	....	...	....
50	1,000	5,667	6,667	1,000	[illegible]
51	1,000	5,667	6,667	1,000	[illegible]
52	1,000	5,667	6,667	1,000	[illegible]
53	1,000	5,667	6,667	1,000	[illegible]

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† The numbers in the table are not strictly correct, for during the time-unit of which has been chosen on the grounds of clearness, the decay does not take formly. A correct treatment presupposes that the time-unit can be neglected in son with the half-value period. The formulae of infinitesimal calculus oper indefinitely small times, within which the decay is strictly constant.

rom the table that the number of UX atoms disintegrating d interval of 5 days is almost double the number disintegrat- irst 5 days, whereas the difference between the numbers for d 9th intervals has already become small, and after about ervals 1,000 atoms decay in 5 days, or, just as many as are Thus the number of UX atoms remaining from the previous als remains constant at 5,667, or, in other words, radioactive has been established. Fifty such time-intervals are 250 proximately the tenfold value of the half-value period of ve already seen that this multiple of the half-value period the attainment of the maximum β-activity of a uranium that has been freed from its content of UX, i.e. for the nt of radioactive equilibrium.

aining how much UX, or another short-lived element, is usually sufficient to express the strength of the preparation urrent units (e.g. 50 scale divisions per minute with a given). We may, however, wish to express how much by weight t-lived element is present, this being always formed in hat are too small to be weighed. This can be done most naking use of the conception of radioactive equilibrium. o the basal assumption of the disintegration theory, the ranium atoms disintegrating per unit of time is equal to of the disintegration constant (λ_1) and the number of atoms $_1$), or $N_1\lambda_1$. Similarly, for the number of UX atoms dis- er unit of time we obtain the product $N_2\lambda_2$, where N_2 is and λ_2 the disintegration constant of the UX atoms. Now that in the state of radioactive equilibrium the number s produced per unit of time is equal to the number disin- d since the former number is equal to that of the uranium egrating per unit of time, it follows that in the state of quilibrium

$$N_1\lambda_1 = N_2\lambda_2.$$

ight of a single uranium atom is known (238 times the tom of hydrogen $= 238 \times 1{\cdot}67 \times 10^{-24} = 3{\cdot}97 \times 10^{-22}$ gm.), ate N_1 by weighing the uranium. λ_1 and λ_2 (see p. 128) are o we may directly obtain the required value of N_2. There r example, in 1 gm. of uranium that has not been chemically least eight months

$$N_1 = \frac{}{3{\cdot}97 \times 10^{-22}} = 2{\cdot}52 \times 10^{21} \text{ atoms,}$$

$$52 \times 10^{21} \times \frac{\lambda_1}{\lambda_2} = \frac{2{\cdot}52 \times 10^{21} \times 5{\cdot}0 \times 10^{-18}}{3{\cdot}3 \times 10^{-7}} = 3{\cdot}82 \times 10^{10}.$$

Since 1 atom of UX weighs $234 \times 1{\cdot}67 \times 10^{-24} = 3{\cdot}91 \times 10^{-22}$ gm., weight of the whole quantity of UX is equal to

$$3{\cdot}82 \times 10^{10} \times 3{\cdot}91 \times 10^{-22} = 1{\cdot}5 \times 10^{-11} \text{ gm.}\dagger$$

It is possible to detect such a very small unweighable quantity the aid of its β-radiation by virtue of the fact that UX disinteg rapidly, and hence emits a relatively large number of β-rays. determining factor for the detection of an element by radioactive mea is not the quantity of it, but the product of the quantity and disintegration constant.

5. Case in which the Life of the Parent Substance is not mu longer than that of the Daughter Element. The Active Depo of Thorium

Whereas the life period of uranium is so large that the quantity remains practically unaltered during the time required to estab radioactive equilibrium with its daughter element, in many cases. in the formation of ThC from ThB, the quantity of the parent substa varies appreciably during the production of the daughter element.

The transformation last mentioned also differs in other impor points from that of uranium. Uranium is available in weigha quantities, and the separation of its transformation product is car out by ordinary chemical methods; every method that is suitable the separation of thorium from uranium is also applicable to the sepa tion of UX (see p. 222). In the case of ThB and ThC, however, we h to do with a parent substance present in unweighable quantities the form of the 'active deposit', which has to be collected by a meth quite new to chemistry.

As already mentioned (p. 1), one of the disintegration products the radium, thorium, and actinium disintegration series is a gase substance called 'emanation'. The emanation of thorium (thor decays with a half-value period of 55 seconds, and the resulting at of thorium A and of its succeeding products are all metallic; the char particles formed by the aggregation of such atoms are held in susp sion in the air for some time, in consequence of their smallness. an only deposited gradually on the surrounding surfaces. These disinte tion products of the emanation further decay with appreciable rapi and are thus strongly active, and it is for this reason that the invi deposit which they form on the surrounding surfaces is called 'active deposit'.‡ As a consequence of their mode of production,

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† If we neglect the difference in atomic weight of the two elements, we can obtain an approximately correct value for the equilibrium quantity by straig inserting the amounts by weight, instead of the numbers of atoms N_1 and N_2.

‡ Since the active deposit exists on the surface of bodies in contact with which

s carry a positive charge (cf. p. 70); this property supplies us ıs of preventing them from being deposited in the direction of gravity. By introducing a negatively charged surface, ıum wire at a potential of −100 volts, into the space in manation decays, and in which the particles are in suspen- ive deposit can be collected upon it.

epresents an arrangement by means of which the active be collected.

llic base and the walls of the vessel are connected to the e of a battery, and the platinum wire ısses through the insulating stopper of connected to the negative pole. If we thorium preparation *D* into the vessel, remove the platinum wire until after several days ('long exposure'), we find α-, β-, and γ-rays, and that its activity h a half-value period of 10·6 hours, in- of which of the types of rays we may is is illustrated by curve *B* in Fig. 43.† e now repeat the experiment with only sure' of a few minutes. We find that shows no initial α-activity after its the activating vessel; but it gradually α-activity, the increase taking place in accordance with g. 43. After about 4 hours the curve reaches a maximum activity then decreases just like that for a long exposure, ılue period of 10·6 hours.

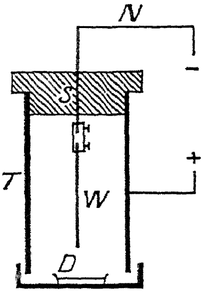

FIG. 42. Apparatus for collecting the Active Deposit.

bvious explanation of this behaviour is that the substance collected on the platinum wire during activation does not ıys, but that these are emitted by the succeeding product ıctivity of the wire thus increases in the same degree as lly formed from the disintegration of ThB. This process ntil radioactive equilibrium has been established between ances, and thenceforward the variation with time of the platinum wire is just the same as if we had been dealing of a long exposure.

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ayed in the form of an exceedingly fine and loose deposit, it can readily other bodies, whereby they acquire radioactive 'contamination'. al nature of the active deposit had been recognized, it was customary acquired by bodies that had been in contact with emanation by the tivity'.

ıte of decay of the activity indicated in curve *B* for the first hour or fact that the state of 'transient equilibrium' between ThB and ThC established (see p. 140).

The measurement of the β-activity of a platinum wire exposed emanation for a short time lends support to the above conclusion. the activity is present right from the beginning, which shows that is a radio-element that emits β-rays.

From the fact that radioactive equilibrium between ThB and is established after a few hours it can be concluded that the half-va period of the latter element is about one hour. The accurate va

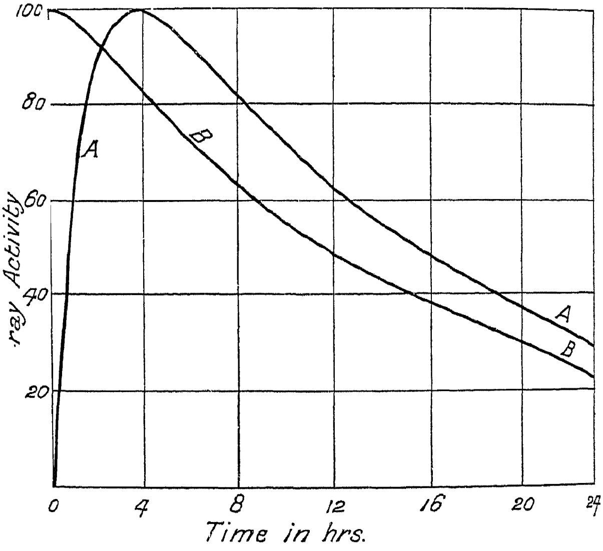

FIG. 43. Variation with Time of the Activity of the Active Deposit of Thorium. after a short (*A*) and after a long (*B*) exposure to thoron.

$T = 60{\cdot}5$ minutes can be calculated from the equation for the cur or it may be obtained by the preparation of pure ThC and the de mination of its decay curve. Thus, if we immerse a small nickel pl in a hydrochloric acid solution of the active deposit, it is found ThC accumulates on the plate, and that it is practically free from Th By following the diminution in intensity of the α-activity of separated ThC we obtain the same value for T as by the calcula referred to above.

'Short' and 'long' exposures are limiting cases; for example, if expose the platinum wire to emanation for an hour, the α-acti still increases initially, but instead of starting from zero it comme at a value intermediate between zero and the maximum value of α-activity. In all cases, however, after radioactive equilibrium been established for some time the activity diminishes with the value period of ThB. The parent substance of longer life grad impresses its period on the daughter element.

aviour can be readily understood when we consider that
of equilibrium just as many ThC atoms disintegrate in
are produced in the same time; but the latter number is
the number of ThB atoms disintegrating, and since this
al to the total number of ThB atoms available, it follows
ber of ThC atoms disintegrating, and this determines the
ill be proportional to the total number of atoms of its
nce.

our just described is very often met with in radioactive
en radon is in equilibrium with radium it disintegrates
lowly with the period of radium, although the half-value
radon is only 3·83 days. Polonium ($T = 140$ days) in
ith RaD disintegrates with a half-value period of 22 years.
lf-value period of the daughter element is only slightly
hat of the parent element, the regular exponential decay
alue period equal to that of the parent element is not
til the lapse of a considerable period after the attainment
m activity. For example, the activity of RaC ($T = 19{\cdot}7$
nishes with a half-value period of more than 30 minutes
d period after the maximum activity has been reached,
th the half-value period of RaB ($T = 26{\cdot}8$ minutes).
e the behaviour of the active deposit of radium is on
more complicated than that of the active deposit of
hall deal with it independently.

e Deposit of Short Life in the Case of Radium

ation (thoron) is not directly transformed into ThB, for
two elements there exists an intermediate product,
4), which could be left out of the above discussion owing
rt period ($T = 0{\cdot}14$ second). This cannot be done, how-
ase of the corresponding radium products. RaA has a
od of 3·05 minutes, a value which, compared with that
minutes) and RaC (19·7 minutes), is too great to be
as the α-activity of a platinum wire that has been given
of about 5 hours in radon decays in the manner indicated
ig. 44. From this we see that it decays rapidly at first,
and more nearly with the period of RaB. After a short
y a few minutes, on the other hand, it decays very rapidly
e period of RaA, as represented by curve II in Fig. 44.
time it remains practically constant, for in this region
lmost completely disintegrated; but almost in the same
nizing action of the RaA ceases the activity of the suc-
creases, for it is being gradually formed and likewise

emits α-rays. Before the RaC has attained equilibrium with the RaB the RaA has completely disintegrated, and thenceforward similar con tions apply to those met with in the thorium series.

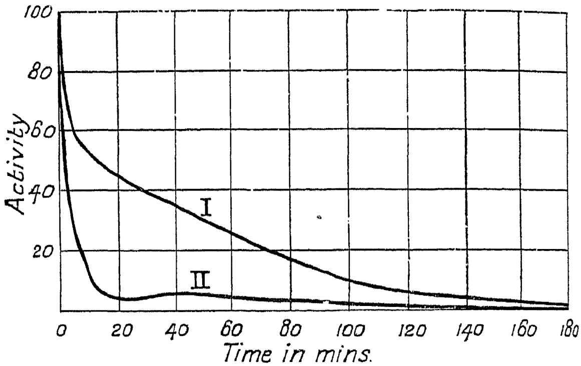

FIG. 44. Variation with Time of the Activity of the Active Deposit of Rad after a long (I) and after a short (II) exposure to radon.

7. Production of an Element of Long Life from one of Short Lif The Long-Lived Active Deposit of Radium

Whereas the active deposit of thorium leads to a product which is least practically stable or completely inactive, in the case of the act deposit of radium we can detect a residual activity even after the lap of a few weeks, when the RaA, RaB, and RaC have completely integrated. Moreover, this activity continuously increases for a re tively long period of time. From the disintegration of the short-li RaC the long-lived product RaD is formed, for which $T = 22$ yea The disintegration of this element leads by way of two further act products (RaE, $T = 5{\cdot}0$ days; and RaF, or polonium, $T = 1$ days) to the stable end-product RaG. The elements RaD, RaE. an RaF are also known collectively as the 'long-lived active deposi radium.†

RaD is a β-rayer the radiation from which can only be detected wi difficulty, so that this is not suitable for the detection of the quanti of RaD available. On the other hand, the succeeding product Ra emits readily detectable β-rays, and they can be made use of for identification and quantitative evaluation of the available quantitie RaD, in much the same way as we can utilize the α-radiation from Th for the identification of its parent substance ThB. In the detectio the amount of RaD present we also frequently revert to the α-radia e third member of the long-lived active deposit, RaF, or

---

† The reason why we can only gradually detect the long-lived active deposit of ra by electroscopic or photographic means is to be found in the extreme softness β-rays from RaD, which is almost inactive.

t the active deposit of thorium in the manner described,
ve at the practical maximum of activity attainable in
, and in the corresponding case of the short-lived active
ium in as short a period as 5 hours. But we should have
long-lived active deposit of radium for over 100 years in
its greatest possible activity. During this time, however,
f radium in our activating vessel, which is the source of
of the active deposit, will have diminished, whereas we
e to regard it hitherto as constant ($T = 1,590$ years). In
f this it can be shown that after the lapse of 110 years
f RaD atoms resulting from a given quantity of radium
ed its maximum value.
om the above considerations that, when we prepare the
preparation possible after an exposure of several hours,
means obtain a strong RaD (or RaF) preparation as a
cay. Large quantities of RaD can be accumulated only
ion of extended intervals of time, as on the walls of a
n which a large quantity of radon has disintegrated, or
arations sealed off in glass tubes, or in minerals and the
tity of RaD in equilibrium with 1 gm. of radium amounts

RaE, which comes between RaD and RaF, can often be left out of
easurements, owing to its relatively short half-value period.

REFERENCES

nts of the topics embodied in this chapter will be found in
tances and their Radiations, by E. RUTHERFORD (Cambridge
1913), in *Radioaktivität*, by ST. MEYER and E. VON SCHWEIDLER
, 1927), and in *Radioactivité*, by Mme P. CURIE (Hermann and

XII

MATHEMATICAL TREATMENT OF DISINTEGRATION PROCESSES

ALTHOUGH the analysis of radioactive processes can sometimes performed graphically, in most cases we have to revert to calculatio We shall therefore briefly discuss in this chapter the mathema treatment of a few of the more important disintegration processes.

1. Disintegration of a Pure Substance

According to the fundamental assumption of the disintegration the the number of atoms disintegrating in unit time is proportional to number of atoms available at the instant considered. From this immediately follows that, if N_0 atoms are present initially, $N_t = N_0 e^{-\lambda t}$ atoms will be available after a time t, where λ is the integration constant and e the base of natural logarithms (cf. p.

Example. Suppose that there are 1,000 relative units of ThB ori ally present (e.g. scale divisions per minute, measured with an electroscope). The number of units remaining after the lapse of hour (= 3,600 seconds) will be $1{,}000 \times e^{-1\cdot 82 \times 10^{-5} \times 3{,}600} = 937$, si $\lambda = 1\cdot 82 \times 10^{-5}$ sec.$^{-1}$

2. Production of a Pure Substance from a Parent Element Con stant in Amount

If we wish to calculate the growth of the daughter element, or fraction of the maximum quantity N_∞ obtainable, after the lapse of time t, we apply the formula:

$$N_t = N_\infty (1 - e^{-\lambda t}).$$

This expression follows immediately from the reciprocal nature of growth and decay curves (cf. p. 128).

Example. Suppose we have mesothorium in equilibrium with its disintegration products up to and including ThA, so that we regard the immediate parent of ThB as being constant in amount then if the maximum quantity of ThB obtainable from this prepara after an 'infinitely' long exposure amounts to 1,000 relative units should have, after an exposure of one hour,

$$N_t = 1{,}000(1 - e^{-1\cdot 82 \times 10^{-5} \times 3{,}600}) = 63 \text{ units.}$$

Substance I, of which there are initially ($t = 0$) A_0 present, the Elements II, III, etc., are successively

›resent the numbers of atoms of the elements II, III, etc., 's B, C, etc. We require to find the magnitudes of A, B, C, ırticular instant of time. Suppose we expose a platinum ım emanation (radon) for a short time, during which prac- RaA is deposited. We measure its initial activity (= amount l calculate how many of the RaB and RaC atoms formed A will be present after the lapse of the time t. The number RaB will be

$$B = A_0 \frac{\lambda_A}{\lambda_B - \lambda_A}\{e^{-\lambda_B t} - e^{-\lambda_A t}\},$$

$$\frac{\lambda_A \lambda_B}{(\lambda_B - \lambda_A)(\lambda_C - \lambda_A)}\Big\} e^{-\lambda_A t} + \left\{\frac{\lambda_A \lambda_B}{(\lambda_C - \lambda_B)(\lambda_A - \lambda_B)}\right\} e^{-\lambda_B}$$
$$+ \left\{\frac{\lambda_A \lambda_B}{(\lambda_A - \lambda_C)(\lambda_B - \lambda_C)}\right\} e^{-\lambda_C t}\Big],$$

, and λ_C are the relevant disintegration constants, and ıe original number of atoms of RaA present.

the time $t = 0$ there were 1,000 atoms of RaA present, minutes ($t = 600$ sec.) there would be 103 atoms of RaA, RaB, and 124 atoms of RaC; the remaining 17 atoms would been transformed into RaD.

me $t = 0$ we have Radioactive Equilibrium between ıformation Products I, II, III, etc.

oms A, B, C, etc., will be present after a definite time t? esponds to a long exposure in radon, and we require to number of atoms of RaA, RaB, and RaC still remaining ım wire t seconds after its removal from the radon.

active equilibrium exists between the several products $= 0$, we must have

$$\lambda_A A_0 = \lambda_B B_0 = \lambda_C C_0 = n_0.$$

e were 1,000 atoms of RaA present initially ($A_0 = 1{,}000$), mbers of atoms of RaB and RaC would be 8,829 and ely.

t the following numbers of atoms will be available:

$$A = \frac{n_0}{\lambda_A} e^{-\lambda_A t},$$

$$B = \frac{n_0}{\lambda_A - \lambda_B}\left[\frac{\lambda_A}{\lambda_B}e^{-\lambda_B t} - e^{-\lambda_A t}\right],$$

$$C = n_0(a\,.\,e^{-\lambda_A t} + b\,.\,e^{-\lambda_B t} + c\,.\,e^{-\lambda_C t}),$$

where

$$a = \frac{}{(\lambda_B - \lambda_A)(\lambda_C - \lambda_A)},\quad b = \frac{\lambda_A}{(\lambda_A - \lambda_B)(\lambda_C - \lambda_B)},\quad c = \frac{\lambda_A \lambda_B}{\lambda_C(\lambda_A - \lambda_C)(\lambda_B -}$$

thus after 10 minutes we should have

$$A = 103, \quad B = 7{,}543, \quad C = 6{,}276.$$

5. 'Secular' and 'Transient' Radioactive Equilibrium

In the previous example the equilibrium quantities of RaA, RaB, RaC have been calculated on the assumption that the radon, from wh the RaA is formed, remains constant in amount, i.e. is itself in eq brium with radium. When this is not the case, as when the exp is made in a vessel that contains only radon, we are no longer justi strictly speaking, in neglecting the rate of decay of the radon as pared with that of the short-lived active deposit. It is true that here we obtain a state of equilibrium between the four products, the relative quantities involved are somewhat different. The bala is in favour of the later products, the decay of which cannot keep with that of the parent substance, so that it is not possible to at 'secular' equilibrium. This state, which is very often met wit practice, is called 'transient' equilibrium. For instance, in the cas radon, the quantities of RaA, RaB, and RaC corresponding to trans equilibrium are respectively about 0·05 per cent., 0·5 per cent. 1 per cent. greater than those corresponding to the state of sec equilibrium. These numbers are calculated from the formulae:

$$\text{for RaA} \quad \frac{\lambda_A}{\lambda_A - \lambda_{Rn}},$$

$$\text{for RaB} \quad \frac{\lambda_A \lambda_B}{(\lambda_A - \lambda_{Rn})(\lambda_B - \lambda_{Rn})},$$

$$\text{for RaC} \quad \frac{\lambda_A \lambda_B \lambda_C}{(\lambda_A - \lambda_{Rn})(\lambda_B - \lambda_{Rn})(\lambda_C - \lambda_{Rn})}.$$

From these formulae we see that the ratio of the equilibrium qua ties corresponding respectively to transient and secular equilibr will become unity in each case when the rate of decay of the par substance can be neglected. The nearer this rate of decay appro to those of the succeeding products, on the other hand, the greater value of the ratio. Thus when we are dealing with the decay of

; in equilibrium with its long-lived parent element radio-correction for the succeeding products ThB, ThC, and ThD unts to from 13 to 15 per cent.

REFERENCES

a with this chapter reference should be made to *Radioactive Sub-ir Radiations*, by E. RUTHERFORD (Cambridge University Press, *ioaktivität*, by ST. MEYER and E. VON SCHWEIDLER (Teubner, and to *Radioactivité*, by Mme P. CURIE (Hermann & Co., Paris,

XIII

THE THREE TRANSFORMATION SERIES

THE investigation of the radioactive transformations on the basis the disintegration theory leads to the result that all natural radioac substances, with the exception of potassium, rubidium, and samari the activity of which elements still demands further investigation. products of disintegration of one or other of the parent substan uranium and thorium. A schematic representation of the success products of the uranium, actinium, and thorium families respecti is given in Tables 34 and 35.

In these tables a radio-element is always placed lower down in table than its parent substance when its production has involved emission of α-radiation; in this case its atomic weight is always units less than that of the parent substance, and this fact is expressed the left-hand column. If the daughter element is the result of the em sion of β-radiation by the parent element, so that its atomic weight is p tically unchanged, it is placed to the right alongside its parent elemen

In certain cases two arrows branch off from the parent elemen indicating that this substance is transformed into two different products. Thus we see that of the two products that are form respectively from RaC, AcC, and ThC, one is produced by the emiss of α-radiation, and the other by the emission of β-radiation. branching in the disintegration process is known as 'dual decay'. 'branching ratio' may differ greatly in different cases. Thus in 10,000 RaC atoms only four are transformed into RaC″, whereas 9 go to form RaC′; the reverse holds for AcC, for which the major of the atoms are transformed into AcC″ (about 9,984 in 10,0 finally, with ThC the difference is less marked, for 65 per cent transformed into ThC′ and 35 per cent. into ThC″, and both bran probably lead to the same stable isotope of lead, thorium D.

The observation of such relatively insignificant branches as th of RaC″ and AcC′ suggests the possibility that there may be o places in the disintegration series at which multiple disintegration take place. Thus the radio-element UZ (see p. 222) has usually b regarded as a branch product of the uranium series; but recent seems to render it more probable that UZ is actually a produc disintegration of an isotope of uranium.

It might be expected that the energy liberated in the transition the C- to the D-products of disintegration would differ according which of the two branches is traversed, i.e. $C \xrightarrow{\beta} C' \xrightarrow{\alpha} D$

TABLE 34

ı-Radium and Uranium-Actinium Disintegration Series

nium I

↓

nium X_1→Uranium X_2→Uranium II

↓

Ionium

↓

Radium

↓

Radon

↓

RaA

↓

RaB→RaC→RaC′

↓ ↓

RaC″→RaD→RaE→RaF

↓

RaG
(Stable
lead
isotope)

ıo-Uranium

↓

ıium Y→Proto-actinium

↓

Actinium→Radio-actinium

↓

Actinium X

↓

Actinon

↓

AcA

↓

AcB→AcC→AcC′

↓ ↓

AcC″→AcD
(Stable lead
isotope)

D. But if the maximum observed β-energy, correspond-
ıer limit of the continuous β-spectrum, be inserted in the
on, it is found that the energy changes along the two
ntical. Thus for the radium disintegration series we

$' = 3{\cdot}1 \times 10^6$ e.V. $\qquad \text{RaC} \xrightarrow{\alpha} \text{RaC}'' = 5{\cdot}4 \times 10^6$ e.V.

$) = \underline{7{\cdot}7 \times 10^6 \text{ e.V.}} \qquad \text{RaC}'' \xrightarrow{\beta} \text{RaD} = 5{\cdot}0 \times 10^6$ e.V.

$10{\cdot}8 \times 10^6$ e.V. $\qquad 10{\cdot}4 \times 10^6$ e.V.

TABLE 35

Thorium Disintegration Series

$$\begin{tikzcd}
\textit{Atomic Weight} & & & & & \\
232 & \text{Thorium} \arrow[d] & & & & \\
228 & \text{Meso-thorium 1} \arrow[r] & \text{Meso-thorium 2} \arrow[r] & \text{Radiothorium} \arrow[d] & & \\
224 & & & \text{Thorium X} \arrow[d] & & \\
220 & & & \text{Thoron} \arrow[d] & & \\
216 & & & \text{ThA} \arrow[d] & & \\
212 & & & \text{ThB} \arrow[r] & \text{ThC} \arrow[r] \arrow[d] & \text{ThC}' \arrow[d] \\
208 & & & & \text{ThC}'' \arrow[r] & \text{ThD}
\end{tikzcd}$$

isotope)

Similar agreement is found also for the branch products of the ac disintegration series, and to a lesser degree for those of the thori series, but not for the β-branching of UX_1, which suggests that UX not a branch product of the disintegration (see above). From th results it seems probable that the D-product formed in each branchi process is independent of the branch traversed.

It should be mentioned in connexion with the uranium-actini series that the identity of the parent substance and the atomic weig of the products are somewhat uncertain. In ordinary lead an isot of mass 207 is always found, and since this originates neither from radium nor from the thorium disintegration series it is assumed t this type of lead is identical with the end-product AcD. The ato weights of the various products of the actinium series in the ab table have been calculated on this basis. The recent discovery of isotope of uranium of mass 235, presumably actino-uranium, g added support to the data embodied in the table.

REFERENCES

Detailed discussion of the subject-matter of this chapter will be foun *Radioactive Substances and their Radiations*, by E. RUTHERFORD (Camb University Press, 1913), and in *Radioaktivität*, by ST. MEYER and E. VON SCHW LER (Teubner, Leipzig, 1927).

XIV

TION OF VERY LONG AND OF VERY SHORT HALF-VALUE PERIODS

periods of the radio-elements vary between very wide
from intervals of time that are inconceivably small
$T = 10^{-11}$ sec.) to periods that are literally enormous
m, $T = 1{\cdot}34\times 10^{10}$ years). Although the determination
cannot be carried out directly, they can nevertheless
a relatively simple manner, and in many cases it is
rmine them in several independent ways.

consider the case of uranium I. If this element is in
h its later disintegration product radium, as is always
erals of great geological age, then (p. 131) the product
of available atoms and the disintegration constant for
ual to the corresponding product for radium,

$$\mathrm{U_I}\times\lambda_{\mathrm{U_I}} = \mathrm{Ra}\times\lambda_{\mathrm{Ra}},$$

ts of the elements be expressed in grams, whereby we
unt of the ratio of the atomic weights (238/226),

$$\mathrm{U_I}\times\lambda_{\mathrm{U_I}} = \frac{238}{226}\times\mathrm{Ra}\times\lambda_{\mathrm{Ra}}.$$

radium and uranium contents of old minerals has been
numerous chemical analyses to be $3{\cdot}4\times 10^{-7}$,† and since
$^{-11}$ sec.$^{-1}$, it follows that

$$\lambda_{\mathrm{U_I}} = 4{\cdot}9\times 10^{-18}\ \mathrm{sec.}^{-1},$$

$$T = 4{\cdot}4\times 10^{9}\ \text{years}.$$

hod which leads to the evaluation of the required
constant is the counting of the number of α-particles
ond by a known quantity of uranium. Since it has been
t each disintegrating atom ejects only one α-particle
s that the number of ejected α-particles, and these can
ust be equal to the number of atoms disintegrating.
isintegration constant is equal to the ratio of the number
egrating per unit of time to the total number of atoms
ent present (p. 126). Now 1 gram ($= 2{\cdot}52\times 10^{21}$ atoms)

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nd for uranium also holds for uranium I, since the amount by weight
ent in uranium is only 0·008 per cent. (see p. 221).

of uranium emits $2{\cdot}4\times10^4$ α-particles per second, half of these due to uranium I and the other half to uranium II. From this we

$$\lambda_{\mathrm{U_I}}=\frac{1{\cdot}2\times10^4}{2{\cdot}52\times10^{21}}=4{\cdot}76\times10^{-18}\ \text{sec.}^{-1},$$

and $$T_{\mathrm{U_I}}=4{\cdot}6\times10^9\ \text{years}.$$

This value is in good agreement with that found by the me previously discussed.

Relation between the Disintegration Constant and the Veloc of the Rays Emitted

A simple empirical relation has been found to exist between the integration constant and the range (or velocity, see p. 21 et seq. radio-elements that emit α-rays. By virtue of this relation we enabled by extrapolation to derive a rough estimate of the disintegra constant even for elements of extremely short life. If, as in Fig. 3 p. 106), we plot the logarithm of the range as abscissa and the logari of the disintegration constant as ordinate, we obtain a straight lin each of the three disintegration series. The range corresponding definite disintegration constant is greater for the actinium series than the thorium series, whilst that for the latter series is greater than range for the uranium series.†

Thus by utilizing Fig. 37 we obtain the value 10^{11} sec.$^{-1}$ for the integration constant of ThC′ from the known range 8·6 cm. at 1 This corresponds to a half-value period of 10^{-11} seconds.

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† The following relation between the disintegration constant and the velocity α-particles emitted can be applied quite generally to all α-rayers:

$$\log\lambda=20{\cdot}46-1{\cdot}191\,.\,10^9\,.\,\frac{Z-2}{v}+4{\cdot}08\,.\,10^6\,.\sqrt{(Z-2)}\,.\sqrt{r},$$

where λ = disintegration constant (sec.$^{-1}$); r = nuclear radius; Z = atomic num v = velocity of the α-particles. Since the α-particle velocity is proportional to it follows that the above relation also connects the disintegration constant range of the α-particles emitted (cf. p. 105).

XV

EMICAL NATURE AND ISOTOPY OF THE RADIO-ELEMENTS

of the radioactive elements, e.g. thorium, uranium, and be obtained in weighable quantities. The determination ties of these elements is carried out by means of the usual thods, for the radioactive nature of the element does not emical properties, and an atom of radium, to take one uring the period of its stability quite analogous to the atoms metals of the alkaline earths. From the moment of its dis- owever, we are no longer dealing with an atom of radium, atom of a new element—the emanation (radon) produced —which, so long as it lasts, behaves completely like the atoms nert gases helium, neon, etc. (See also footnote, p. 161.)

majority of the radio-elements can only be obtained in quantities, and in many cases the amounts of them avail- invisible. How then was it possible to obtain information cal nature of these substances?

ple of the method adopted consisted in adding a known o the solution containing infinitesimal traces of the radio- e investigated, and then precipitating it with a suitable the solution had been thoroughly mixed. After filtration pic examination of the precipitate and of the solution tion to dryness revealed whether or not the radio-element ried down by the element *A* in the above operation. If recipitate was again dissolved, and another element (*B*) mical properties was added, after which a separation of undertaken. In this way it would be found with which of ances *A* or *B* the radio-element was separated, and hence, point of analytical chemistry, to which of them it had the blance. By a continuation of this process it was always d the element most nearly resembling the unknown radio- chemical reactions. It is necessary to emphasize, however, usions which were drawn about the chemical nature of a from this 'co-precipitation' process did not carry convic- as proved that non-specific adsorption forces do not play a ocess. In Chapter XVII we shall deal with the rules which ehaviour of such small quantities of a substance; in point vere first disclosed by the study of the radio-elements.

ove described process of finding for every radio-element that known element which most closely resembles it has in many cases elicited a surprisingly simple result. With very many of the radio-elements it has been found, for instance, that their resemblance to a particular element is so great that, after admixture of this element, it has not been possible by any process to separate them again. It has in fact proved impossible, by fractional crystallization of this element, to achieve even the slightest increase in concentration of the radio-element in a particular fraction. The radio-element and the admixed inactive element behaved completely like a single chemical individual.

The phenomenon could only be explained by what was then quite a novel assumption, that the atoms of the radio-element have the same chemical properties as those of the inactive element, but that the two differ from each other in atomic weight and radioactive behaviour. On this theory the radio-element was only a particular type of the known element; from the chemical point of view it was not a new element, but belonged to the same place in the periodic classification of the elements. For this reason it was called an 'isotope' of the more common element.

This phenomenon of isotopy was discovered simultaneously also in the field of the inactive elements. To-day we know that the majority of the ordinary elements consist of more than of one kind of atom, and we shall have more to say on the phenomenon of isotopy for common elements in Chapter XIX. For them the difference between the isotopic types of atom of one and the same element lies only in their weights. For this reason alone the phenomenon of isotopy among the radio-elements is of a unique and particularly interesting kind, for here the various atomic types differ not only in their weights but also in their different ability to disintegrate. Moreover, in the field of the ordinary elements we always find a uniform mixture of the isotopic types of atoms, whereas with the radio-elements, although they sometimes occur in association with their inactive isotopes, as in the cases of radium D and ionium, in the vast majority of cases they can also be prepared free from their inactive isotopes. Because of this fact, in particular, the radio-elements have been found suitable for the study of the essential properties of isotopes, and in what follows we shall discuss a few of these investigations in greater detail.

If, for instance, we endeavour to separate or to concentrate the RaD contained in lead chloride derived from pitchblende, we find that we are no nearer our goal after numerous crystallizations of known lead compounds, or by partial sublimation of these compounds or of the metallic lead. Other methods are equally fruitless, such as electrolysis in aqueous solution or in the fused state, adsorption by charcoal or other substances, diffusion, dialysis, and so on. The difficulty of separating closely related substances like those of the rare earths is a phenomenon well known in chemistry, but the difficulty of separation in such cases is not to be compared with that confronted when we are dealing with isotopes. We can always appreciably displace the concentration ratio in a mixture of the rare earths by means of various chemical operations, but this is not possible with isotopes unless we have recourse to special methods (cf. Chap. XX), although the quantitative determination of the ratio of the constituents, especially for the rare earths, is often faced with great difficulties, quite unknown in radiochemistry. Thus we can find the RaD-content of a lead-RaD mixture in a most convenient and accurate manner by means of an electroscope, and using the α-radiation of its succeeding product polonium (see p. 136).

If we do not proceed from a natural mixture of RaD and lead such as is found in minerals, but prepare a mixture artificially by mixing a pure RaD salt, obtained from the decay of the gaseous emanation, with a lead salt, we find that this mixture likewise shows the behaviour described above.

In consequence of the ease with which it can be detected, RaD is particularly suitable for the control of the concentration ratio of a mixture of lead isotopes before and after the application of chemical operations. Nevertheless, in the investigation of the properties of an unmixed isotope—e.g. its spectral behaviour, the absolute solubility of its salts, its density, its normal electrochemical potential, etc., and above all its atomic weight—the stable end-product of the uranium series RaG is to be preferred, for although it is inactive, it is an isotope of lead that can be obtained in much greater quantities.

Pure RaG is obtained from uranium minerals that have not been contaminated by common lead in the course of geological time, for example, from a crystalline uraninite from East Africa. Owing to the smallness of the quantity of RaD that can be obtained from radium emanation, it is not possible to carry out an atomic weight determination of this isotope of lead, and our conclusions as to the difference of the atomic weights of RaD and common lead (atomic weight = 207·21) are based solely on the formula

$$\begin{array}{ccccc}(\text{At. wt. of Ra}) & - & 4\times(\text{At. wt. of He}) & = & (\text{At. wt. of RaD}).\\ 226 & & 16 & & 210\end{array}$$

But in the case of RaG it has been possible to establish experimentally that its atomic weight is different from that for common lead. The value 206·03 was found for the atomic weight of RaG, whereas the value predicted by calculation[†] was

$$\begin{array}{ccccc}(\text{At. wt. of Ra}) & - & 5\times(\text{At. wt. of He}) & = & (\text{At. wt. of RaG}).\\ 226 & & 20 & & 206\end{array}$$

[†] In exact calculations of this kind the decrease in mass due to the loss of energy has to be taken into account. In the gradual transformation of uranium into lead,

Most uranium minerals, e.g. pitchblende from Joachimstal, contain ordinary lead in addition to numerous other mineralogical impurities and under the most favourable conditions we obtain from this mineral a mixture of about 36 per cent. of lead with 64 per cent. of RaG, with a 'combining weight' of 206·4. On the other hand, the mineral curite (containing 21·3 per cent. PbO and 74·2 per cent. UO_3), which occurs in large quantity at Katanga (Belgian Congo), contains no trace of ordinary lead, and the lead extracted from it is pure radium G.

The specific gravity of metallic RaG is related to that of common lead in the same ratio as their atomic weights, from which it follows that the atomic volumes of the two elements are equal. This is shown in Table 36.

TABLE 36

Atomic Volumes of Different Types of Lead

Type of lead	*Atomic weight*	*Specific gravity*	*Atomic volume*
Ordinary lead. .	207·21	11·337	18·28
Uranium-lead (RaG)	206·03	11·273	18·28

From the fact that the density of a saturated solution of RaG nitrate in water is correspondingly smaller than that of ordinary lead nitrate in water it follows that the molar solubilities of these two substances are equal (see Table 37). Moreover, no difference has been detected in the refractive indices of the saturated solutions, as is also indicated in Table 37.

TABLE 37

Saturated Aqueous Solutions of the Different Types of Lead

Salt	*Molar concentration*	*Refractive index*
Ordinary lead nitrate .	1·7993	1·7815
Uranium-lead nitrate .	1·7991	1·7814

The normal electrochemical potential of RaG in a solution of $RaG(NO_3)_2$ is at least within 1/10 milli-volt identical with that of lead in a solution of $Pb(NO_3)_2$. The mobility of these two ions is identical within

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8 α-rays and 6 β-rays are emitted, with a total kinetic energy of 52×10^6 e.V., which represents a loss of mass of 0·056 (see Table 57). We should expect, therefore, that the atomic weight of pure RaG would be

$$238{\cdot}07_4 - 8 \times 4{\cdot}002 - 0{\cdot}056 = 206{\cdot}00_2,$$

If allowance be made for the probable percentage content of actino-uranium (^{235}U) in uranium (*c.* 1%), the atomic weight of U_1 becomes $238{\cdot}10_5$, and that of RaG becomes $206{\cdot}03_3$ [1].

1/100 per cent. The X-ray spectra are also the same to a degree of accuracy of about 1/200 per cent. of the wave-length, whereas the optical spectrum reveals only exceedingly small differences. The melting-points do not differ by more than 0·06° C. The temperature of commencement of superconductivity for ordinary lead (7·2° A.) was found to be identical within 1/40° with that at which superconductivity begins with uranium-lead. Moreover, no difference could be detected in the form of the resistance curves between 7·2° and 15° A. Thus for two isotopic mixtures of mercury obtained artificially and differing in combining weight by 0·1 of a unit, the resistance was found to be the same to within $1:10^6$.

Still another isotope of lead, ThD, the end-product of the thorium series, is obtainable in weighable quantities. It should possess an atomic weight of $232-(6\times 4) = 208$. Unfortunately, the large majority of thorium minerals also contain uranium (sometimes also common lead), and hence we obtain from these minerals a mixture of RaG with ThD, in consequence of which the atomic weight appears to be greatly reduced. The purest ThD hitherto obtained was separated from a thorite from Norway containing practically no uranium, and it yielded a combining weight of 207·9.

Of the remaining isotopes, ionium is the only one (excepting protoactinium) that can be obtained in weighable quantities. It is isotopic with thorium. Io-Th mixtures prepared from Joachimstal pitchblende and having an ionium content of *c.* 30 per cent. possess a combining weight of 231·51, whereas thorium has an atomic weight of 232·12.

All the known isotopes of radioactive elements are listed together in Table 38, which also contains the atomic weights and half-value periods of the substances concerned. The grouping of the elements was carried out in most cases on the basis of chemical experiments described at the beginning of this chapter, namely, by establishing their inseparability from known substances. In the case of the substances of shortest life recourse had to be made to the radioactive 'displacement law' discussed in the next chapter. Each group is arranged in the order of diminishing half-value period, and begins with the member of longest life, from which, in general, it receives its name. Thus we speak of 'types of lead', 'types of thorium', and so on. We notice that the table, in which the elements gold and mercury are included for purposes of completeness, embraces only the last two horizontal rows of the periodic classification (cf. Tables 40 and 41, pp. 158, 159, which present the entire periodic system of the elements). The isotopes of mercury and of other non-radioactive substances are referred to in Chapter XIX.

TABL

Radioactive Isotopes (with Atom

Period	*Group I*	*Group II*	*Group III*	
VI	79	80	81	
	Au 197·2 stable	Hg 200·61 stable	Tl 204·39 stable	Pb stable
			AcC″ 207 4·76 minutes	RaG 206 stable
			ThC″ 208 3·1 minutes	ThD 208 stable
			RaC″ 210 1·32 minutes	AcD 207 stable
				RaD 210 22 years
				ThB 212 10·6 hours
				AcB 211 36·0 minutes
				RaB 214 26·8 minutes
VII	87	88	89	90
		Ra 226·0 1,590 years	Ac 227 13·5 years	Th 232·1 $1{\cdot}34 \times 10^{10}$ years
		$MsTh_1$ 228 6·7 years	$MsTh_2$ 228 6·13 hours	Io 230 $8{\cdot}3 \times 10^4$ years
		AcX 223 11·2 days		RdTh 228 1·90 years
		ThX 224 3·64 days		UX_1 234 24·5 days
				RdAc 227 18·9 days
				UY 231 24·6 hours

Weights and Half-Value Periods)

Group V	Group VI	Group VII	Group VIII (0)
83	84	85	86
Bi 209·00 stable	Po 210 140 days		Rn 222 3·825 days
RaE 210 5·0 days	RaA 218 3·05 minutes		Tn 220 54·5 seconds
ThC 212 60·5 minutes	ThA 216 0·14 seconds		An 219 3·9 seconds
RaC 214 19·7 minutes	AcA 215 0·002 seconds		
AcC 211 2·16 minutes	AcC′ 211 5×10^{-3} seconds		
	RaC′ 214 10^{-6} seconds		
	ThC′ 212 10^{-11} seconds		
91	92		
Pa 231 $3{\cdot}2 \times 10^{4}$ years	U_I 238·07 $4{\cdot}4 \times 10^{9}$ years		
UZ 234 6·7 hours	AcU 235 c. 7×10^{8} years		
UX_2 234 1·14 minutes	U_{II} 234 $3{\cdot}4 \times 10^{5}$ years		

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XVI

THE PLACE OF THE RADIO-ELEMENTS IN THE PERIODIC CLASSIFICATION OF THE ELEMENTS. THE DISPLACEMENT LAW

THE discovery of the large number of about forty radioactive substances brought chemists face to face with the problem as to the possibility of accommodating these substances in the periodic classification of the elements. A method for the rational grouping of the radio-elements suggests itself, as revealed in Table 38, when we take the phenomena of isotopy as the basis of our considerations. According to this, most of the radio-elements are chemically inseparable from other radioactive elements or from stable elements. If we adhere to the principle of assigning isotopes to one and the same place in the periodic classification, it is found that from uranium to thallium the number of available places in the classification suffices for the accommodation of all the radio-elements.

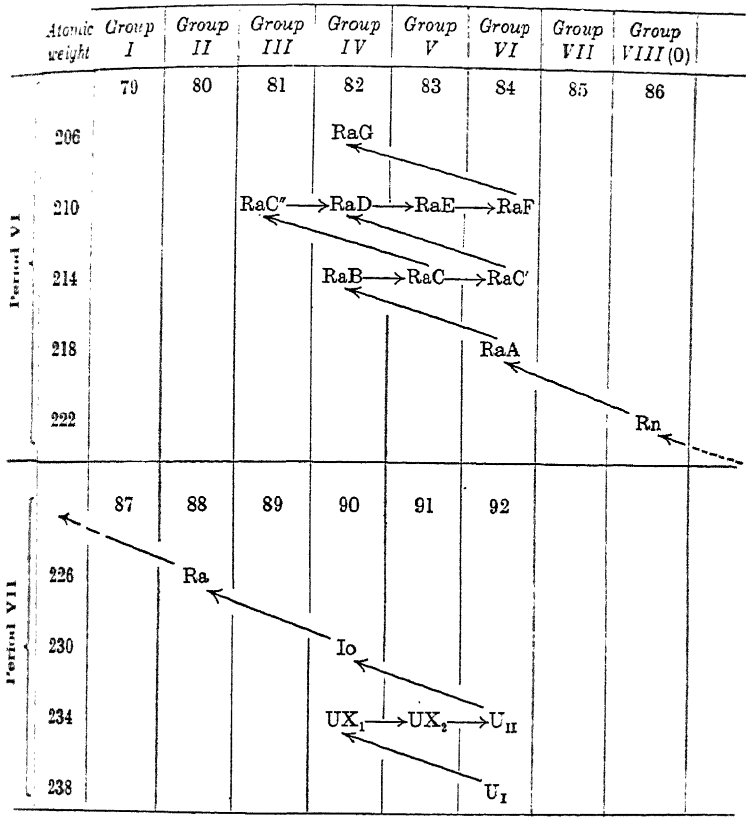
A particularly important relation is revealed when we apply this method of grouping the radio-elements to obtain the solution of the question as to what changes in the chemical nature of the elements ensue from the emission of α- or of β-particles. In other words, how does the chemical nature of the radio-elements change as we pass from one element to another within a transformation series? We are enabled to recognize the required relation by comparing Tables 34 and 35 (pp. 143, 144) which give the sequence of and type of radiation emitted by the radio-elements, with Table 38, which shows the positions of the radio-elements in the periodic classification. Such a comparison leads to the following 'displacement law':

The emission of an α-particle gives rise to the formation of an element situated two places lower down in the natural sequence of the elements than the disintegrating element, whereas the emission of a β-particle leads to the formation of an element that is situated one place higher in the system.

In this consideration we regard the whole of the chemical elements as being arranged in a continuous series, in much the same way as they were represented by Lothar Meyer in his atomic volume curve (cf. Fig. 24, p. 64). In Mendeléeff's table we must remember that the individual periods are only portions of this continuous series, and that consequently the transition of an element in the zero group to a position situated two places lower down in the series signifies the appearance of an element in the sixth group of the preceding horizontal row. If this is clear, Table 39 will be immediately intelligible. It shows the

TABLE 39

Arrangement of the Uranium-Radium Series in the Periodic Classification



uranium-radium series arranged in the last two horizontal rows of the periodic classification. In this table an arrow directed towards the left, and always embracing two groups, indicates the emission of an α-particle, whereas an arrow directed to the right, and reaching only the next group, signifies a β-transformation. Corresponding to the diminution in atomic weight, the arrows representing α-transformations are inclined to the horizontal. In particular, we notice that for RaC, which suffers 'dual' disintegration (see p. 142), the displacement law holds both for the product resulting from the emission of an α-particle and for that attendant upon a β-disintegration; i.e. RaC″ is situated two places lower and RaC′ one place higher than RaC. The validity of the displacement law for the actinium and for the thorium series can be represented diagrammatically in an analogous manner, but can also be directly deduced from a comparison of Tables 34 and 3 or 35 and 38.†

From the displacement law it follows that when an α-transformation is succeeded by two β-transformations within one and the same disintegration series, the result must always be an isotope, as in the transition of U_I via UX_1 and UX_2 into U_{II}, which is isotopic with U_I. Two isotopes that are genetically related in this way must necessarily exhibit a difference in atomic weight of four units (= one α-particle), and from the consideration of such cases it is eminently clear that the atomic weight cannot be the determining factor in deciding the position of an element in the periodic classification. This conclusion is in splendid agreement with the views on the constitution of the atom already discussed in Chapter VIII. According to these, the position of an element in the periodic classification, or the 'atomic number' of an element, does not depend directly on its atomic weight, but primarily on the magnitude of the electrical charge of its atomic nucleus.

On the basis of this theory of atomic structure the radioactive displacement law follows as a matter of course. As a result of the emission of an α-particle, the charge on the nucleus diminishes by two positive units, and the newly formed element must therefore be situated two places lower in the periodic classification. A β-transformation, on the other hand, connotes an increase in the nuclear charge by one unit, since the production of a β-particle accompanies the transformation, in the nucleus, of a neutron into a proton (see Chap. IX, p. 94). From this it follows that the emission of a β-particle results in the formation of an element situated one place higher in the periodic classification. The successive loss of one α- and two β-particles must accordingly lead us back to the initial nuclear charge value. In other words, an isotope must be formed which is by four units lighter in atomic weight, as in the above-mentioned case of U_I and U_{II}.

It has been mentioned in earlier chapters (see p. 63 and p. 32) that a direct experimental evaluation of the nuclear charge for most of the elements has been possible from the investigation of X-ray spectra and of the scattering of the α-rays. From the viewpoint of the periodic classification the following results of these investigations were of especial interest.

(1) Isotopes like RaG and Pb have the same nuclear charge, and hence their insertion in one and the same place of the periodic classification is fully justified. Differences between them are based on the fact

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† Conversely, it has been mentioned (p. 146) that for the radio-elements of shortest life, the recognition of their chemical nature and their consequent inclusion in the table of isotopes were only rendered possible by the assumption of the validity of the displacement law.

that, although they have the same nuclear charge, the number or at least the arrangement of the structural components of the nucleus is different.

(2) Speaking generally, the chemical elements should be arranged in the sequence of their atomic weights; but it has long been known that this rule stands in contradiction to the chemical nature of the elements in three places in the periodic classification. For the three pairs of elements, argon-potassium, tellurium-iodine, and cobalt-nickel, the heavier element had to precede the lighter in the classification. This sequence of the elements in the periodic classification, established on the basis of their chemical behaviour, entirely corresponds to the succession of the nuclear charge values. Accordingly, if the value of the nuclear charge, instead of the atomic weight, be taken as the basis of the arrangement of the elements in the classification, the contradiction above referred to vanishes.

(3) In the interval between hydrogen (1) and uranium (92) the bearers of all the 92 nuclear charge values are known, with the exception of four. The missing elements have the atomic numbers:

43. eka-manganese;
61. rare earth;
85. eka-iodine;
87. eka-caesium.

These are the only chemical elements still unknown. Thus whereas there is possibly a large number of isotopes still to be discovered, the detection of new elements, apart from the four mentioned above, is only to be expected if elements exist with yet higher nuclear charge value than that of uranium (cf. p. 117 et seq.). The investigations described thus lead to the important result that we are able quite definitely to limit the expectations of chemistry, which had to proceed essentially in an inductive manner in its search for new elements, even after the formulation of the periodic classification.

From X-ray spectra we can, in the first place, fix only the atomic number of the missing elements. Here we may compare Fig. 24 (p. 64), which at once reveals that the regularity of the straight line would be immediately interrupted if, in the four stated positions of the abscissa, we were not to leave gaps for the elements yet unknown, but plot the values of the ordinates for the succeeding elements. On the other hand, we cannot gain information directly from the atomic number about the chemical nature of an element, because from amongst the four 'atomic analogues' of Mendeléef knowledge of the atomic number enlightens us only as to the 'horizontal neighbours', but not as to the 'group neighbours' of the element, and these are still more are the valency, which can only amount to a small integral number 1 to 4), directly from the velocity of diffusion. From the constants of diffusion 0·33, 0·46, and 0·66 cm.^{2} day^{-1} for radioactinium (thorium isotope), actinium (homologue of lanthanum), and actinium X (isotope of radium) respectively, we can for instance calculate that the respective valencies are 4, 3, and 2.

Diffusion experiments further show that under certain circumstances radio-elements can exist in the colloidal form. Thus in neutral and in weakly acid solution polonium is partially colloidal; it diffuses slowly, does not dialyse through a parchment membrane, and so on. This behaviour serves as the basis of a method of concentrating the polonium in radio-lead; the polonium remains behind in the dialyser, and the crystalloidal lead diffuses outwards through the parchment.

Isotopes of bismuth, too, show such a marked tendency to appear in colloidal form that when we filter a neutral or weakly acid solution of ThB–ThC, the latter (a type of bismuth) is for the most part retained by the filter.

A particularly striking confirmation of the colloidal nature of the solution of some of the radio-elements has been furnished by the following observation. When ions or other colloids of opposite sign are added to the solutions, the phenomena of the inversion of charge and precipitation characteristic of colloids are obtained in exactly the manner to be expected in such cases. Moreover, it has been proved by means of the photographic plate that radioactive colloidal particles have an invariable tendency to aggregation and sedimentation.

The molecular weight of the emanations (radon, thoron, actinon) can be approximately determined by observation of the velocity with which they flow through small orifices, and in this way, for actinon, values lying between 222 and 218 have been obtained.

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^{10}Be and ^{10}B). Moreover, for any future theory of the structure of t
atomic nucleus, the following result found for light atoms will be
importance, to wit, those types of atoms whose mass-numbers amou
to a multiple of 4 show no excess in atomic weight above integral valu
(relative to $^{16}O = 16{\cdot}000$), whereas the intervening atomic nuclei
show such an excess in mass, and hence they appear to have a l
stable structure.

Finally, it is a particularly surprising fact that the combining weigh
of all the elements appear to be natural constants, in spite of the lar
number of isotopes of which many of them are composed. (On th
point see Chap. XXI, p. 200 et seq.)

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important for the prediction of chemical properties. But since its position in the periodic classification is fixed by the atomic number we can also recognize the chemical nature of the missing elements by making use of this classification. This we have already done above by using the terminology 'eka' introduced by Mendeléef for the higher homologue.

Tables 40 and 41 represent the periodic classification of the elements on the basis of these results, Table 40 giving a 'long-period' and Table 41 a 'short-period' mode of presentation. Both forms have been given since each offers advantages for the consideration of certain regularities. Thus the long-period form is to be recommended in all considerations related to the theory of atomic structure (cf. Table [illegible] in Chapter VIII), whereas the short-period form epitomizes in a clear way particularly the laws of chemical valency.

It should be mentioned that the elements hafnium (72) and rhenium (75) were discovered only in recent years, and on the basis of the conclusions just described. At the time when the method of determining the atomic number with the aid of X-ray spectroscopy became known, it was necessary, in allotting atomic numbers to the chemical elements, to leave gaps not only in the above-mentioned four positions, but also in the positions 72 and 75. In the case of the element 75 (rhenium) the regularities in the periodic classification referred to above allowed definite predictions on the chemical nature of the missing substance to be made, so that the element could be looked for with success. The periodic classification in its old form allowed no decision to be arrived at as to whether the element 72 (hafnium) was one of the rare earth metals, or a homologue of zirconium. A reliable statement in the sense of the latter alternative was first rendered possible by the theory of atomic structure (cf. Table 22, p. 85). For both elements the first and at the same time the most certain proof that the missing substances were present in the mineral mixture under investigation resulted from observation of the X-ray spectrum. X-ray spectroscopy, accordingly, has proved its worth not only in revealing the gaps in the periodic classification of the elements, but also as a tool in analytical chemistry, and without it the successful search for elements yet undiscovered would have been rendered incomparably more difficult, if not quite impossible.

Information has already been given in Table 38 (p. 152) on the different forms in which the elements of the last two horizontal rows of the periodic classification occur, beginning with thallium. The isotopes of the inactive elements are shown in Table 43 (p. 182). (See Chapter XIX.)

XVII

THE CHEMICAL BEHAVIOUR OF EXTREMELY SMALL QUANTITIES OF A SUBSTANCE

From the genetic relation existing between the radio-elements it follows that we can obtain only extremely small quantities of any radio-elements of short life (see radioactive equilibrium, p. 131). Thus if we possess a quantity of radium as large as one gram, under the most favourable circumstances we can obtain from it about 13 mg. of the relatively long-lived radio-element RaD, whereas we can obtain only 0·22 mg. of polonium, and as little as 10^{-16} mg. of the very short-lived RaC″. For this reason the chemistry of the short-lived radio-elements is a chemistry of substances available in extremely small quantities, and therein lies its particular uniqueness.[†] From amongst the reactions especially characteristic of every chemical element, those of a spectral or other optical nature are generally inapplicable, as their sensitiveness is insufficient. We are restricted to the determination of the solubility of the elements and of their compounds, or to that of their electrochemical behaviour and the like, whereas the usual methods of chemistry always have to be supplemented by electroscopic measurements.

1. The Solubility and Velocity of Solution of Extremely Small Quantities

Owing to the smallness of the amounts available, we cannot prepare a saturated solution of the short-lived radio-elements, and hence the direct determination of the solubility is not possible. But we can determine the relative velocity of solution. Thus if we immerse the surface, say a piece of gold sheet, on which we have collected the active deposit of radium, into a dilute solution of an acid for only a few seconds, we find that a greater fraction of the atoms of RaB than of RaC have gone into solution, whereas the fraction of RaA atoms dissolved is still smaller. The electrochemical nature of these substances thus diminishes down the series RaA → RaC → RaB, in accordance with the chemical behaviour we should expect for the elements Po → Bi → Pb.

In individual cases we can also infer from the velocity of solution the existence of definite compounds of the radio-elements concerned. For example, from the much smaller velocity of solution of the ThB deposited on the anode, as compared with that on the cathode, we can infer the existence of a ThB-peroxide of difficult solubility on the anode.

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[*] The property of radioactivity influences the chemical behaviour only in the case of strong activities, and then in the same way as an external source would do (see Chap. XXIV, § 5).

This conclusion is confirmed by the observation that this difference in the velocities of solution can be annulled by the addition of a reducing agent to the acid used as solvent.

2. The Electrolytic Deposition of Small Quantities

The converse process to the solution of a metal is to be found in the electrolytic deposition. Thus if we electrolyse a solution of the active deposit of radium, RaA is deposited most readily, and RaB only with difficulty. If we perform the electrolysis with a small current, i.e. if we keep above a certain value of the cathode potential, it is possible to separate electrolytically the most noble of the available radio-elements in a very pure state. This method is of great importance especially in the preparation of polonium, which can be obtained in this way from solutions of the salts of 'radio-lead', as these contain an isotope of bismuth (RaE) and three isotopes of lead (RaD, RaG, Pb), in addition to Po. Further details are given on p. 214. Instead of by electrolysis the separation of the radio-elements can also be effected by dipping a less noble metal into the solution of the radio-element concerned; this is analogous to the deposition of copper from a solution of a copper salt on a sheet of zinc. In radioactive investigations we very often require a preparation of RaC free from RaB. This can be obtained in the simplest manner by dipping a small sheet of nickel into an acid solution of the active deposit of radium which no longer contains the short-lived radio-element RaA.

Both the methods described lead to the establishment of a potential series of the radio-elements, the most noble member of which is polonium, and the least noble radium.

3. Determination of the Solubility of the Salts of Radio-elements by means of the Methods of Adsorption and Precipitation

The chemical behaviour of an element is characterized primarily by the solubility of its different compounds. In order to gain information about the chemical nature of the radio-elements it was therefore necessary to establish the solubility relations of their compounds. In the case of the short-lived elements, which are present only in quantities too small to be weighed, this was not possible by the study of their pure salts, but only by adsorption and co-precipitation methods, in combination with theoretical considerations.

The Method of Adsorption.

If we shake up a salt of low solubility, e.g. $BaSO_4$, with an aqueous solution of a salt the sulphate of which is readily soluble, e.g. bismuth sulphate, we find that an interchange takes place between the Ba-ions situated at the surface of the solid salt and the Bi-ions of the solution. Now the forces that strive to bind Bi- and SO_4-ions together to form a solid salt are much smaller than those operative in binding together Ba- and SO_4-ions. This follows from the much greater solubility of bismuth sulphate in dilute acids.† When the Bi-ions collide with the adsorbent they will only rarely be held by the SO_4-groups, and hence the adsorption will be small. The behaviour will be different, however, when the solution contains a salt such as $RaCl_2$, the cation of which forms with SO_4 a compound of low solubility. In this case the interchange between the Ra- and the Ba-ions at the crystal surface will be a very active one, and the radium will be bound or adsorbed by the surface of the $BaSO_4$. We can express this generally by saying:

A cation will be adsorbed by a salt of low solubility when it forms with the anion of the adsorbing salt a compound, the solubility of which in the solvent is small. The less the solubilities of the relevant compound and the adsorbent, the stronger will be the adsorption.

By means of this method it can be readily proved, for instance, that ThX and AcX (both types of Ra) form sulphates of very low solubility, and that the 'B'-products (types of lead) give rise to sulphates of fairly low solubility; on the other hand, the sulphates of the 'C'-products (types of Bi) and also of polonium are readily soluble. If the experiments are carried out in potassium hydroxide, in which the solubility of lead sulphate is known to be greater than that of bismuth sulphate, a correspondingly weaker adsorption of the B-products is found than of the C-products.

The Method of Precipitation.

Instead of establishing which salt of low solubility adsorbs the radio-element concerned, we may also proceed along the following closely related course. A soluble barium salt is added to the solution of the radio-elements, say the active deposit of thorium, and the Ba precipitated as sulphate. Whereas the ThB is also precipitated, the ThC remains in solution, from which we may likewise infer that the first compound (lead sulphate) is only soluble with difficulty, whilst the latter compound (bismuth sulphate) is readily soluble. *A radio-element will be precipitated in greater measure with a deposit of low solubility, the less soluble is its compound with the negative constituent (anion) of the precipitate.*

From the results of experiments on adsorption and precipitation it seems to follow that for the extremely small quantities involved in the case of the radio-elements, the essential condition for their inclusion in the precipitate is primarily their low solubility. But more recent vestigations have shown that the size and electric charge of the sur of the adsorbent are also weighty factors in adsorption. Moreover problems of co-precipitation, an important part seems to be played the question as to whether the compound of the radio-element and anion of the precipitate is isomorphous with the crystals of the pre pitate, so that it can form mixed crystals with them. The relati are here so complicated that it is not yet possible to formulate ru embodying all processes in a unified scheme.

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† More accurately expressed, it is not solely a question of the magnitude of the forces binding the ions together in the crystal lattice, but of the excess of these forces over those which seek to bind the ions to molecules of water, or to hydrate the ions.

4. Volatility of Extremely Small Quantities

The observation of the proportion in which the different compon of the active deposit volatilize when heated for a short time at hi temperature enables us to form a conclusion as to the sequence of th boiling-points of the radio-elements concerned, or of their compoun Thus in air at 700° C. none of the 'C'-products volatilize, whereas th 'B'-products are already appreciably volatile; from this it follows th ThB-oxide is more volatile than the oxide of ThC (lead and bismu oxides respectively). This method can also be applied for the parti separation of radio-elements of short life.

Nevertheless, an accurate determination of the boiling-point extremely small quantities is not possible, chiefly owing to the pr ponderance of the process of sublimation. Thus a quantity of rad of the order of 1 curie = 0·65 mm.^{3} manifests a sharply defined boili point at −62° C. and a freezing-point at −71° C., but quantities radon of the order of 10^{-7} curie no longer possess a definite boili point. Such small quantities already begin to sublime apprecia at −164° C., and at −125° C. practically no condensation at all ca be recognized.

5. Velocity of Diffusion. Determination of Valency and the Degree of Dispersion. Colloidal Radio-elements

The determination of the velocity of diffusion in water of the io of all the radio-elements with a half-value period not very much le than one hour can be performed by the usual method. In fact, th extremely small concentration is of particular advantage here, seein that we have to operate with solutions as dilute as possible.

We can likewise determine with little difficulty the electroly mobility, or the velocity with which the radioactive ions move in a electric field of unit gradient. The ratio of this to the velocity of diffu sion immediately reveals to us the charge carried by the ion concerne and hence its valency. Since the mobilities of the majority of inorga ions differ among themselves by only a few per cent., we can also eval are the valency, which can only amount to a small integral number 1 to 4), directly from the velocity of diffusion. From the constants of diffusion 0·33, 0·46, and 0·66 cm.^{2} day^{-1} for radioactinium (thorium isotope), actinium (homologue of lanthanum), and actinium X (isotope of radium) respectively, we can for instance calculate that the respective valencies are 4, 3, and 2.

Diffusion experiments further show that under certain circumstances radio-elements can exist in the colloidal form. Thus in neutral and in weakly acid solution polonium is partially colloidal; it diffuses slowly, does not dialyse through a parchment membrane, and so on. This behaviour serves as the basis of a method of concentrating the polonium in radio-lead; the polonium remains behind in the dialyser, and the crystalloidal lead diffuses outwards through the parchment.

Isotopes of bismuth, too, show such a marked tendency to appear in colloidal form that when we filter a neutral or weakly acid solution of ThB–ThC, the latter (a type of bismuth) is for the most part retained by the filter.

A particularly striking confirmation of the colloidal nature of the solution of some of the radio-elements has been furnished by the following observation. When ions or other colloids of opposite sign are added to the solutions, the phenomena of the inversion of charge and precipitation characteristic of colloids are obtained in exactly the manner to be expected in such cases. Moreover, it has been proved by means of the photographic plate that radioactive colloidal particles have an invariable tendency to aggregation and sedimentation.

The molecular weight of the emanations (radon, thoron, actinon) can be approximately determined by observation of the velocity with which they flow through small orifices, and in this way, for actinon, values lying between 222 and 218 have been obtained.

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XVIII

APPLICATION OF THE RADIO-ELEMENTS AS INDICATORS IN PHYSICAL, CHEMICAL, AND BIOLOGICAL INVESTIGATIONS

As we have seen, many difficulties had to be overcome before the chemical nature of the natural radio-elements could be recognized. But now that we know the nature of all of them with great certainty we can apply them conversely to obtain information on the behaviour of known substances in such small concentrations that they cannot be investigated by ordinary methods. Elements such as lead and bismuth, which exist both in the form of a stable type and as radioactive isotopes, are particularly amenable to investigations of this kind, for here it is possible, by mixing in varying proportions the stable element with a radioactive isotope, to bridge over the whole range from quantities that can only be detected by radioactive means to quantities that can be weighed. In this manner we are able to investigate completely the behaviour of one and the same chemical element over a very wide range. In problems of this kind, in which the radio-element is not the object but the agent of the investigation, we say that the radio-elements serve as 'indicators'.

In the choice of a radio-element suitable as an indicator it is advisable in general to find one that can be detected in quantities as small as possible. We must bear in mind, however, that the half-value period (T) varies in inverse proportion to the strength of the radiation (see Chap. XII), and that an element that is measurable in small amounts necessarily possesses a short half-value period. For this reason it would never be possible to make use of say RaC′ ($T = 10^{-6}$ sec.) or the more strongly active ThC′ ($T = 10^{-11}$ sec.) as indicators. Moreover, the only three indicators available for the element thallium are already too short-lived for many experiments.

It follows that for our present purposes we cannot draw upon all the radio-elements. Only those included in Table 42 have any practical application, and the ones most frequently to be recommended are printed in italics.

Radio-elements like ionium, uranium X_1, and uranium X_2, which have no inactive isotopes, are also frequently of service, for with their aid we can raise the intensity of the radiation of their less virile isotopes which, although themselves radioactive, have a longer life and are therefore less active and more difficult to measure. Thus uranium X_1 is mentioned in the table as an indicator capable of being used for thorium. In the same way we can apply thorium X as an indicator

TABLE 42

Radioactive Indicators

Atomic number	*Element*	*Indicator*
81	Thallium	Radium C'' Thorium C'' *Actinium* C''
82	Lead	Radium B *Radium D* *Thorium B* Actinium B
83	Bismuth	Radium C *Radium E* *Thorium C* Actinium C
84	Polonium	Radium A
86	Radon	*Thoron* Actinon
88	Radium	*Thorium X* Actinium X
89	Actinium	Mesothorium 2
90	Thorium	Ionium Radiothorium Radioactinium *Uranium* X_1
91	Proto-actinium	Uranium X_2

for radium, and radium A for polonium. But radium and polonium themselves can also be used as 'indicators' in some investigations; for if in the narrower sense we understand the application of the radio-elements as 'indicators' to mean that it only refers to experiments in which a radio-element takes the place of its active or inactive isotope, then in the broader sense this expression can also be used for all those experiments in which a radio-element serves as an aid in the examination of the behaviour of matter present in the smallest amounts.

In addition to the natural radio-elements hitherto considered, the recently discovered and artificially produced radio-elements can also be used as indicators. As explained more fully in Chapter X, the bombardment of certain of the elements by α-particles results in the production of radioactive substances which emit positrons when they disintegrate; and in the bombardment of almost all the elements by neutrons new types of atoms are formed, which are transformed by the emission of electrons. Provided that these artificial radio-elements are produced in sufficient quantity to be detectable with ease, and that they have a period of life reckoned in minutes or more, they are straightway adapted also to be used as radioactive indicators. Although the discovery of the artificial radio-elements is of quite recent date, there are already available a significant number of investigations on these lines, and there can be no doubt that in the future the artificial radio-elements will surpass the natural radio-elements in their importance as indicators, for in the study of practically all the elements in the periodic classification they place at our disposal the corresponding active isotopes, including those of carbon, phosphorus, sodium, calcium, iron, etc., which are of especial importance in biological experiments. Sometimes it is even possible to produce the radioactivity directly in the chemical compound of the element to be investigated [1].

It may be mentioned that in those rare cases in which inactive isotopes are readily accessible they can be used as indicators in fundamentally the same manner, though other methods of measurement must be used. Thus instead of making electrometric measurements it is necessary to determine the density or to make determinations of the thermal conductivity, and so forth. Such experiments have been carried out with deuterium ^{2}D and the oxygen and nitrogen isotopes ^{17}O, and ^{15}N but further discussion of them does not belong here.

The applications of 'radio-elements as indicators' fall mainly into three groups; with their aid:

(A) We can study the behaviour of minute quantities of a radio-element, or of an indicated element,† down to invisible and unweighable amounts.

(B) We can determine very small fractions of an indicated substance which has been separated from the main part by solution, diffusion, etc.

(C) By mixing only a fraction of a stable element with its radioactive isotope we can differentiate this fraction from the rest of the element, and then *study the exchange of atoms of identical chemical properties*. It is especially this use of indicated atoms which opens the door to otherwise insoluble problems.

A. THE STUDY OF MINUTE QUANTITIES OF AN ELEMENT

A problem frequently met with in analytical chemistry is the distribution of traces of an element between precipitate and solution; minute amounts of many elements are included either by co-precipitation or by adsorption on the crystals of a precipitate or, conversely, remain dissolved when the bulk of the element is removed. In the case of radio-elements or indicated elements such an imponderable quantity can be determined without the slightest difficulty. Studies of this type have shown that methods of chemical separation, which are reliable for normal weights of matter handled in an analytical laboratory, fail in the collection of small amounts.

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† An *indicated element* is an element containing a small amount of an isotopic element, which serves as an indicator for the purpose of detection or measurement.

For example, if we want to determine the lead content of ordinary rocks or meteorites, which is only of the order of a thousandth of one per cent., we find its quantitative separation practically impossible; in this case the application of radium D as an indicator has proved to be very useful. For this purpose a known amount of RaD was added to the solution of the material, and by electrolysis this was deposited anodically as RaD O_2 together with the contained lead. Thus, if in this process only 80 per cent. of the amount of RaD originally added were regained by electrolysis, it follows that the yield of the lead analysis was likewise only to the extent of 80 per cent., so that the mass of the deposit must be increased by 25 per cent. in order to obtain a quantitative value for the lead content of the rock.

In this simple example the radio-element RaD serves directly as an indicator of the element to be estimated, i.e. lead. But the range of application of the radioactive method in analytical chemistry can be extended considerably if the element lead, activated by the radio-element ThB, is in its turn only the reagent for the substance (e.g. ammonia) in which we are interested. This method of 'Radiometric Microanalysis' has rendered it possible, for instance, to carry out a determination of the nitrogen content of organic substances to the order of magnitude of some ten-thousandths of a milligram. The decomposition of the organic substance with sulphuric acid and the distillation from caustic soda of the ammonia formed is essentially the same as in the well-known micro-Kjeldahl process, except that several special precautions have to be taken, corresponding to the higher sensitivity aimed at. The ammonia distilled over is collected in a standardized (but not radioactively activated) solution of lead nitrate; the precipitated lead hydroxide is centrifuged off, and then, in aliquot parts of the solution, the lead that has not been precipitated is determined with the help of a radioactive indicator method. This is done by mixing each 1 c.c. of the solution, freed from the precipitate by centrifuging, with 0·5 c.c. of a radioactivated N/1,000 solution of lead nitrate, and then precipitating with 0·5 c.c. of a N/1,000 solution of potassium chromate. It follows from the fundamental facts of isotopy that the indicator substance ThB that has been added with the 0·5 c.c. of the lead nitrate solution will be distributed between the precipitate and the solution in accordance with the available amount of total lead. Hence the more lead there is present in the lead solution under estimation, i.e. the less ammonia there has been introduced into it, the greater will be the activity remaining in the solution. By distilling over known amounts of ammonia and maintaining always the same conditions of experiment, the electroscope can be calibrated directly in terms of ammonia.

B. THE DETERMINATION OF VERY SMALL FRACTIONS OF AN INDICATED SUBSTANCE

The solubility of lead chromate at room temperature is too small to be determined with accuracy by gravimetric methods. It is of course possible to fall back on conductivity measurements or to calculate the solubility product from equilibrium constants; but for concentrations so small as that of a saturated solution of lead chromate both of these methods are tedious and subject to several sources of error. On the other hand, with the help of a radioactive indicator we can determine the solubility of lead chromate just as readily as we can perform a simple weighing operation. For this purpose we add a definite quantity of ThB to a known amount of a soluble lead salt. The radioactivity of this indicated substance can be measured in terms of any arbitrary unit such as the number of scale divisions per minute obtained with the electroscope used. Thus if 10,000 such units of ThB have been thoroughly mixed with 10 mg. of lead, it is clear that one unit of ThB will then always necessarily indicate the presence of 0·001 mg. lead. Now we can prepare lead chromate from the artificially activated lead by the usual chemical methods. If we have kept the saturated solution of this compound sufficiently long in a thermostat at the desired temperature we can determine its concentration by evaporating to dryness a few c.c. of the solution, and measuring with the electroscope the activity of the almost invisible residue. A special advantage of the method is that the presence of foreign ions interferes in no way with the measurements, for of course only the radioactive substance influences the electroscope.

Another problem in which a very small quantity of the initial amount of an element had to be detected was encountered in the search for the hydride of bismuth, the analogue of arsine and stibine. As a result of many fruitless attempts to prepare it, the conclusion was reached that, if it could be prepared at all, this compound would only be obtainable in amounts corresponding to vanishingly small fractions of the initial quantities of material used, and that it would thus readily escape detection by the usual chemical methods. But the sensitivity of radioactive measurements can be graded down so far as to encompass both qualitatively and quantitatively even the ten-millionth part of the initial amount of the substance. This enormous extension of the range of measurement is necessary if we are to study the condensation and revolatilization of bismuth hydride; but the fact of its existence can be shown by relatively simple means, and even as a lecture experiment. When magnesium filings are coated with the bismuth isotopes ThC or RaC and dissolved in dilute hydrochloric acid, the volatile hydrides of these radio-elements are evolved, and can be condensed at the temperature of liquid air, or decomposed in a hot glass tube and measured. By means of the radioactive method just described it was possible to accumulate experience as to the best mode of preparation and on the degree of stability of bismuth hydride, and it was but a short step to the long-aspired goal of preparing this compound also from inactive bismuth by similarly dissolving a magnesium-bismuth alloy in hydrochloric acid. It may be mentioned that the quantity of bismuth with which the existence of this volatile compound was first recognized amounted to only 10^{-15} gm., and that it has been found possible with the help of radioactive indicators to detect the existence also of gaseous lead hydride, the yield of which is still smaller.

Technical investigations can also benefit from the application of radioactive indicators. It has been found possible to determine with speed and accuracy and quantitatively the different permeabilities to air of almost completely air-tight gummed materials (gas-mask fabrics) by using air containing traces of radon. For precipitates in which radium is imbedded, an alteration in their surfaces can be recognized simply and with certainty from the change in their emanating power in respect of radon. This method has been shown to be one of much promise in the solution of practical problems, such as the examination of the condition of the surface of glass.

In the treatment of syphilis, by making use of radium E as an indicator, the retention of bismuth in the organism was investigated in detail. For a long time after treatment a considerable amount of the metal remains in the body, maintaining an anti-syphilitic effect; the important matter was to gain information as to the rate at which different bismuth compounds are resorbed after injection. A further investigation concerned the retention of lead (indicator: ThB or RaD) and of thorium (indicator: UX_1 or Io) both in human and animal bodies; extended to the behaviour of tumours, it proved that cancerous tissues retained appreciably larger amounts of bismuth than the corresponding healthy tissue.

While in the examples quoted the problem was to determine fractions of the original substance, an experiment may be mentioned in which the total amount of a substance is unknown, but can be inferred from an activity measurement of a fractional part of it. The flow of water in a river can be determined by adding a small quantity of a radium salt as an indicator [2]. For this purpose it is only necessary to allow the radioactive solution to flow for a given time at constant rate into it, the greater will be the activity remaining in the solution. By distilling over known amounts of ammonia and maintaining always the same conditions of experiment, the electroscope can be calibrated directly in terms of ammonia.

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In a similar manner, attempts have been made to determine the quantity of blood in living animals, but in comparison these experiments are much more prone to the objection that part of the radioactive substance may be lost by adsorption and chemical exchange.

C. The Exchange of Atoms of Identical Chemical Properties

The interchange of atoms and molecules within a homogeneous substance can be followed *only* by means of isotopic indicators. The simplest example of such a kinetic problem is presented by the addition of an activated solution of $Pb(NO_3)_2$ to an inactive solution of $PbCl_2$ of equivalent strength. By crystallizing from this mixture a sample of lead chloride, we can determine whether it contains not only lead atoms which were linked with chlorine before the mixing, but also lead atoms originally combined in the form of nitrate. As we should expect, according to the theory of electrolytic dissociation, the result of such a determination demonstrates that the lead atoms in the crystallized lead chloride are derived in equal numbers from the two initial solutions. On the other hand, let us say, if activated lead nitrate and inactive tetraphenyl-lead, or another compound in which the lead atom is linked with carbon in a non-ionizable form, be simultaneously dissolved and then separated by crystallization, we are unable to detect any interchange of the lead atoms between the lead nitrate and the organic compound of lead.

In an analogous manner it has been possible to show that the charges of di-valent and tetra-valent lead ions are interchanged with the greatest of ease. After the discovery of artificial radioactivity it was also feasible to establish the same phenomenon with manganese ions of different valency, and to examine also the firmness of binding of iodine, bromine, etc., in organic compounds, as well as to study the mechanism of important reactions in organic chemistry. For instance, in the case of a molecule containing iodine, it was possible, by the use of iodine activated artificially, to give an affirmative answer to the question as to whether the racemization of an optically active compound is preceded by a substitution [3].

The interchange between the solid and liquid phases, as between metal and ion, or between a salt and its saturated solution, is more difficult to picture, and for this reason even more important to investigate than the positional interchange in solutions. These processes, as functions of time, can be readily followed by means of radioactive indicators; and such investigations can be made the basis of a method of measuring the surface area of powders, which is of importance in experiments on adsorption. This method is based on the fact that when a radio-element is added to a saturated solution of the isotopic adsorbent, in the form of powder, it must distribute itself uniformly in a very short time between the molecules of the dissolved part of the adsorbent and the molecules of the outermost layer of the undissolved part of the powder. From the diminution of the radioactivity of the solution in this way we can easily calculate the dimensions of the surface of the powder. The surface areas of lead sulphate, lead sulphide, bismuth phosphate, and of many other compounds have been measured in such a manner, and with the aid of the data so obtained it has been possible to prove that, for all these adsorbents, the limit of adsorption is reached before the adsorbed substance has formed a coherent layer even one molecule thick on the surface of the adsorbent.

Closely related is the method which made possible, by the use of radio-elements, an experimental investigation of the process of 'self-diffusion'. Here we are concerned with the fact predicted by the kinetic theory of matter that the atoms (or molecules) of a homogeneous gas or of a liquid move amongst themselves according to the same laws as govern the diffusion of one element into another. But since in the process of self-diffusion the objective properties of the element investigated remain entirely unchanged, this process could previously be carried out only as a 'conceptual experiment'. Not until the introduction of radioactive indicators was it possible to open up to observational study the phenomenon of self-diffusion. In performing the experiment, a lead cylinder was fused into a hard glass tube, three-quarters of the length of the cylinder consisting of ordinary lead and the remaining quarter of activated lead. For experiments of short duration ThB was used as indicator, whereas for those of long duration RaD was chosen. By carefully melting the lead in the tube and maintaining it at liquefying temperature for several days the indicated active atoms of lead were intermingled with the other lead atoms by diffusion; it was possible after solidification to investigate the distribution of the activity established in the column of lead during the experiment, and the constant of self-diffusion in molten lead could be calculated by the usual methods. By application of specially sensitive methods it was also possible to measure the coefficient of self-diffusion in solid lead. When RaD atoms are deposited on the surface of a thin sheet of lead they gradually diffuse into it, and this process can be followed by observation of the diminution in the number of scintillations or of the ionization due to α-rays emitted by the succeeding product polonium.

In a similar way we can follow the change in position of the lead ions in heated crystalline lead chloride, and thence draw conclusions about the processes of diffusion and conduction of electricity in crystals.

After the discovery of artificial radioactivity it was possible to examine the circulation of phosphorus in human or animal systems.[4] The active form of phosphorus was produced from sulphur, and the atoms of phosphorus in food could be indicated by the addition to them of sodium phosphate of known activity. In this manner it was established, for instance, that in the course of 5 days, 22 per cent. of the phosphorus atoms in a man's food are evacuated by the kidneys and 16 per cent. by the bowels, whereas when the phosphorus atoms are introduced directly into the blood-stream the corresponding proportions eliminated are respectively 20·5 per cent. and 2·5 per cent. in the same time. The remainder of the phosphorus atoms enter into the structure of various organs, and above all into the bones, whence they are sooner or later displaced by the arrival of fresh phosphorus atoms. It was possible to measure the rates of formation of various organic phosphorus compounds (viz. phosphorus esters, lecithin, etc.) present in the blood and in the different organs, as well as to determine the distribution of the phosphorus atoms taken up into the system between individual bones, muscles, liver, kidneys, teeth, and so on. The study of the behaviour of the phosphorus in the brain was of special interest. If some ten hours after administration of radioactive sodium phosphate to rats or other animals the phosphatides of the brain are extracted, they are found to contain radioactive phosphorus atoms. Now we know that phosphorus atoms present in a phosphatide molecule take no part in simple exchange processes; therefore the radioactive phosphorus atoms can only have entered these molecules during their synthesis. Hence, from the presence of radioactive phosphatides in the brain tissue of fully grown animals after the intake of radioactive sodium phosphate, we can conclude that these tissues, contrary to general assumption, are constantly regenerated; presumably the lecithin molecule, under enzyme action, is broken down and rebuilt.

Analogous experiments undertaken with maize and sunflowers showed that most of the phosphorus atoms are found in the leaves, and that they are mobile. Investigation revealed that an individual phosphorus atom which is to-day situated in one leaf in the course of a few days will very probably be found in another leaf, while in seeds no exchange takes place between the phosphorus atoms of the germ and of the endosperm [5].

In conclusion it may be emphasized that in the measurement of the rays we are not confined to electrical methods, for sometimes the observation of scintillations or photographic methods are to be preferred. We have already given one example of the application of the scintillation screen in connexion with the measurement of the coefficient of self-diffusion in solid lead. The photographic plate may offer special advantages over the electroscope in so far as with it the particular spot at which a chemical change has taken place can be rendered visible. When an investigation was made, in experiments previously described, into the kinetic interchange of molecules between the crystals of a solid substance and an activated saturated solution of the substance, it was found that for certain crystals the number of molecules taking part in the exchange was distinctly smaller than the number of molecules comprising the outermost layer of the crystals. This proved that the kinetic exchange takes place only at privileged positions in the surface. The actual positions could not of course be found by means of the electroscope used in this investigation, because only the total effect of all the rays is measured by the electroscope. But when the crystals were allowed to act on a photographic plate, it was immediately revealed that the radioactive atoms were situated almost wholly at the edges of the crystals, so that the exchange between the crystals and the radioactive solution had taken place at these edges. In this way the seat of reactions can be recognized to a nicety.

The examples we have given should suffice to show that the method of radioactive indicators is capable of multifarious applications. It is to be hoped that in the future an increasing number of workers will make use of these indicators and in this way facilitate the solution of many problems.

In particular, it is perhaps not superfluous to emphasize that such experiments involve by no means heavy costs. As will be seen from the above examples, many of the experiments have been carried out with thorium B or thorium C as indicators. Both of these substances are themselves quite short-lived ($T_{\mathrm{ThB}} = 10{\cdot}6$ hours; $T_{\mathrm{ThC}} = 60{\cdot}5$ minutes) and the quantities of radioactive substance used in the individual experiments have therefore practically no monetary value, for these amounts are freshly obtained before each experiment from the parent substance radiothorium (see p. 216 et seq.), which itself remains completely unchanged and only decays with a half-value period $T = 1{\cdot}90$ years. Since '1 mg.' radiothorium (i.e. a quantity whose γ-radiation is equivalent to that of 1 mg. radium) supplies an adequate amount of ThB and ThC for almost all indicator experiments, and this quantity is always for the most part regenerated 24 hours after removal of the preparation from the radiothorium, it is possible with '1 mg.' radiothorium to perform an indicator experiment daily either with ThB or with ThC throughout a period of several years. At the present time '1 mg.' radiothorium costs about eight pounds. In many experiments distinctly smaller amounts of radiothorium will suffice; on the other hand of course there are also experiments in which greater activities are desirable, just as occasionally it is also impossible to avoid using other indicators like RaD and RaE, which are more difficult to obtain.

The acquisition also of artificial radio-elements as indicators does not necessarily involve large monetary expenditure, especially when, as is often the case, radon can be obtained from hospitals and similar institutions. A small glass tube filled as full as possible with very finely grained beryllium powder and with radon constitutes a source of neutrons which can be used for several days for the production of artificial radio-elements. For many experiments quantities of about [illegible] millicuries of radon suffice; for others, however, hundreds of millicuries of radon are necessary, and still stronger active preparations can be obtained by bombardment with deuterons that have been accelerated say in a cyclotron (see p. 290). When a source of neutrons is required for continuous use it is of course desirable to mix a salt of radium instead of radon with beryllium powder. The costs can frequently be reduced by renting radium for a specified period instead of buying it.

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XIX

ISOTOPY OF ELEMENTS WHICH ARE NOT RADIOACTIVE

In Chapter XV a description was given of how the phenomenon of isotopy was discovered for the radioactive elements. Isotopes are substances that differ from each other in respect of their radioactive properties and atomic weights, but in general they cannot be separated from each other by chemical means. From this it was necessary to draw the conclusion that the inability to resolve an element chemically does not constitute proof of the law formulated by Dalton, according to which the atoms of one and the same element all have the same weight. It was a curious coincidence in point of time that the factual incorrectness of Dalton's assumption was proved simultaneously by other investigations. Although these researches, which establish the existence of isotopes in the field of the non-radioactive elements, are only loosely connected with the theme of this book, we shall briefly discuss the principle of the methods used and the results obtained, because they are of great importance in a consideration of the position of the radioactive atoms within the entire system of the elements.

The first indication that an element can contain atoms of different weight was found in the study of positive rays for the case of neon. The systematic development of these investigations led to the construction of the 'mass spectrograph'. For those elements that consist of a mixture of different types of atoms, this apparatus enables us to establish individually the masses of these atomic types, whereas it is well known that the chemical methods for the determination of the 'atomic weight' only yield mean values in the case of mixed elements. For this reason it is better to use the term 'combining weight' instead of 'atomic weight' (see Chap. XXI).

The following principle lies at the basis of the mass spectrograph: The element to be investigated is subjected to electrical discharge in a highly evacuated tube, whereby its molecules and atoms in part assume one or more positive charges, and as positive rays they travel towards the cathode and pass through a slit in this into the experimental chamber. Here the particles are first deflected by an electrostatic field and then they pass through a magnetic field so arranged that deflexion now takes place in the opposite direction, and they finally strike a photographic plate. By suitable choice of the strengths of the electric and magnetic fields, and by the use of suitable diaphragms and an appropriate position of the photographic plate, it can be ensured that all the particles with a constant value of m/e are brought to the same place on the photographic plate, even when their velocities fluct within a certain range. When particles of the same mass m bea double electric charge, they are deflected to another position on photographic plate, in fact, to the same place as all particles of mas and single charge e would strike. In this connexion the termin of optical spectroscopy is applied, and the mass spectra so obtained designated as spectra of the first, second, and higher orders. The va of m/e corresponding to the individual lines is found by compari with the neighbouring lines of known atoms and molecules such as CO, CO_2, O_2. The sensitivity of the method is so great that in majority of cases an isotopic mixture in the proportion of 999:1 still be recognized as a mixture of two types of atoms.

The photogram represented in Fig. 45 (Plate IV), which is taken fr the publications of Aston, gives an idea of the sharpness with wh these mass spectra can be obtained. For precisional determinati somewhat different methods developed by Dempster and by Bainbri are also found to be particularly suitable. The former is based on the fa that the charged atoms all traverse the same potential difference an so acquire the same energy, so that when they pass through a magne field, particles of equal mass and having the same velocity are brou into the collecting electrometric system without any special focus device. If particles of different mass are present, and the magne field is held constant, they can be collected in turn according to th masses by appropriate adjustment of the accelerating potential, required value of which is inversely proportional to the mass.

The 'whole number rule' was the most important result brought light even by the earliest mass-spectroscopic investigations, and it h been consistently confirmed by the results of later experiments. this we mean that the atomic weights of all types of atoms approxim very closely to whole numbers, when we assume the atomic weight ^{16}O to be equal to 16·0000. Thus the large deviation in the atomic of chlorine (35·457) from an integral value is due to the fact th chlorine consists of two isotopic types of atom in the proportion 76 per cent. of ^{35}Cl to 24 per cent. of ^{37}Cl. A marked deviation of th combining weight of an element from an integral value is thus in its proof of the fact that we are dealing with a mixed element. Converse however, when the combining weight of an element is almost integr in value, we are not necessarily justified in concluding that we ar dealing with a pure element. Bromine is an example of this, for contains almost equal numbers of atoms of mass 79 and 81, so that combining weight lies very close to the value 80.

That integral numbers occupy a privileged position in the matter of atomic weights can be readily understood from current ideas on th

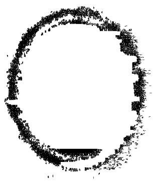

FIG. 52 (p. 270)
Normal Pleochroic Halo in Biotite
(Magnification c. 520)

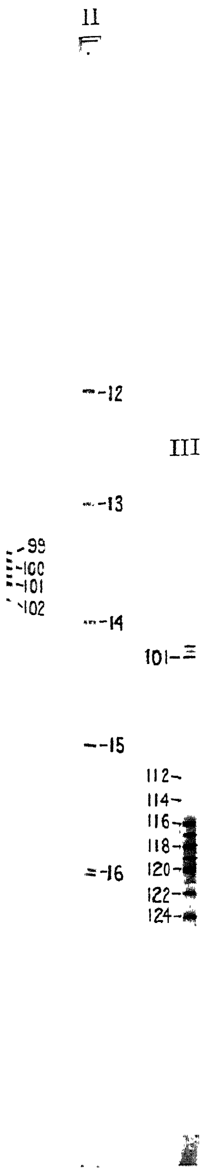

FIG. 45 (p. 178). Mass Spectra (I shows the second order mass-spectrum of Hg; II shows the lines of C, CH, CH_2, CH_3, CH_4, and that of ^{16}O directly alongside the last of these; III shows the 11 isotopes of tin, as well as xenon lines).

structure of atomic nuclei, since they are assumed to consist of only protons and neutrons (see Chap. IX). For practical as well as for theoretical reasons it is therefore advantageous to introduce the concept of 'mass-number' in addition to those of combining weight and atomic weight. From the practical point of view the mass-number is the whole number which lies nearest to the atomic weight; and in the theory of atomic structure it denotes the numerical sum of the protons and neutrons in the nucleus of the atom.

It is to be expected on theoretical grounds that the whole number rule will hold only as a first approximation, and deviations from it are of great importance in relation to the nuclear structure of the atom. Since in all theoretical considerations we are less concerned with the absolute than with the relative magnitude of the deviations from integral values, the idea of the 'packing fraction' has been introduced, by which we understand the difference between the mass of the atom and the integral part of its mass-number, divided by the mass-number. The packing fraction of ^{16}O is of course zero, since the masses of the atoms are referred to $^{16}O = 16{\cdot}0000$. Elements lighter than oxygen have positive values of the packing fraction; thus ^{1}H has a packing fraction 0·0081, and ^{4}He the value 0·00098. The atomic masses 20 to 200 (neon to mercury) have negative packing fractions; thus Sn has the value −0·00073. The heaviest elements again have positive values of the packing fraction, as with thallium +0·00018. As has been discussed in greater detail in Chapter X, the stability of atomic nuclei and the possibility of their mutual transmutation are related most intimately with these small differences in mass, so that one of the most important problems in mass-spectroscopy is the evaluation of them with the greatest possible accuracy.

None of the methods of mass spectroscopy is sufficiently sensitive to detect an isotopic atomic constituent when its proportion is considerably less than 0·001 of that of the isotope most strongly represented. As regards the existence of atomic types that are present in an element in such relatively small quantities, important information has been obtained by the examination of optical spectra.

In line spectra the differences due to the different masses of the isotopes generally lie beyond the limit of measurement. A very important exception to this is found in the case of hydrogen, whose heavier isotope ^{2}D has been recognized by a displacement of the lines of the Balmer series. By using spectrographs of very high resolving power, however, and studying the fine structure of line spectra, it has been possible with other elements also to obtain information on the existence and relative abundance of their isotopes. The isotope of lead 204 [1], five isotopes of platinum [2], and an isotope of lutecium [3] have been detected by this method, although the abundance of the last-named amounts to only 1·5 per cent.

In the case of band spectra it was to be expected on theoretical grounds that distinct differences between isotopic molecules must reveal themselves, for some of the constituent lines arise from the rotation of the molecules and the vibrations of the component atoms, and these depend directly on the mass. By virtue of the extraordinary sensitivity of spectroscopic methods it has been possible not only to confirm by photographs of band spectra the existence of isotopes already found by the mass-spectrograph, but in recent years constituents have been observed in the band spectra of various elements which could only be interpreted by the assumption of hitherto unknown isotopes (e.g. ^{13}C, ^{15}N, ^{17}O, and ^{18}O) that remain invisible in mass-spectrograms owing to the small amounts of them present.

Moreover, the experiments on the artificial transmutation of the elements have introduced us to a large number of additional isotopes. But most of them are radioactive and do not occur in nature (see Chap. X); for this reason they are not included in Table 43. An exception has been made only in the cases of ^{3}T, ^{3}He, and ^{10}Be. Up to the present these elements are only represented among the atomic types prepared artificially, but as they are presumably stable there is some probability that they will be found in nature.

There is another reason, however, why the study of the artificial transformations of the atom is also very important for our understanding of the stable isotopes. When we realize artificially the transition of one atom into another and can measure the yield of energy that occurs in the process, we are in a position to calculate from this the relative masses of the two atoms to a higher degree of accuracy than is possible by measuring up mass spectra (see Chap. X, p. 124). From amongst the masses of the light atoms (up to oxygen) given in Table 43 only ^{1}H, ^{2}D, ^{4}He, ^{10}B, ^{12}C, and ^{14}N have been determined by mass-spectroscopic means, whereas the other masses have been calculated from the energy relations of the transformations of these elements into each other, produced artificially [4].

All the stable types of atoms that have been established by one of the methods mentioned are inserted in Table 43 with their mass-numbers. The precisional values of the atomic weights, or, what is the same thing, the deviations of the atomic weights from the integral values of the mass-numbers, have been introduced only for the elements up to argon, in order to keep the table within reasonable limits. For many of the heavy elements there are as yet available no precisional determinations of approximately the same degree of accuracy. As well as the mass-numbers, the table also contains the relative proportions the isotopes present in the elements occurring in nature, and in many cases these can be derived with considerable accuracy from mass-spectrograms, by making use of photometric records.

When both the precisional values of the masses of its isotopes and also their quantitative relative abundance are known for an element, it is of course possible to calculate from this the combining weight of the element, and thus to test the values established by chemists in quite an independent way. If the greatest accuracy is required, it is necessary in this calculation to take account of the fact that the basis of the units of atomic weight in chemistry is not quite the same as that in physics. In chemistry the fictitious 'atomic weight' of the mixed element oxygen, which is in reality a mean value of the weights of the pure oxygen isotopes corresponding to their relative abundance, is taken to be 16·0000, whereas in physics the value 16·0000 is ascribed to the mass of the oxygen isotope ^{16}O. Since the mixed element oxygen contains atoms of ^{18}O along with atoms ^{16}O in the relative proportions of 1 to 630 (^{17}O is so feebly represented that its influence can be neglected), the combining weight of the mixed element oxygen is, from the physical viewpoint, fixed at too low a value by the factor 0·9997. For this reason all the combining weights of mixed elements calculated on the basis of physical atomic weights must be multiplied by this factor in order that they may agree with the chemical scale of combining weights. In the last two columns of Table 43, for all elements for which sufficient data are already available for the purpose, the combining weights are given side by side as calculated on the one hand from the isotopic constitution, and on the other hand as determined directly by chemical means. It is seen that the agreement in most cases is excellent. It should be mentioned that in the case of several elements the calculation based on the isotopic constitution pointed to the fact that the combining weight determined by chemical methods was in need of revision.

The large amount of material on isotopes contained in Table 43 cannot yet be interpreted in its entirety from the theoretical point of view, but there is no doubt that the values of the relative abundance of the types of atom present in the individual elements give important clues concerning the stability of the relevant atomic nuclei (cf. Chap. X). Thus it is a very striking fact that elements with odd atomic number have on the average by no means so many isotopes as those elements with even atomic number. Only in the case of a single element of odd atomic number (potassium) has it been possible to detect a third isotope (^{40}K) with certainty (see p. 237), but its relative amount is so small (1 in 8,000) [5] that we can formulate the general rule that elements of odd atomic number never possess more than two isotopes present

TABLE 43

Isotopes of the Elements

Atomic number	Element	Symbol	Mass-number	Atomic weight	Abundance in %	Combining weight (oxygen = 16): Calculated from isotopic composition	Combining weight (oxygen = 16): Determined directly
0	Neutron	*n*	1	1·0090	..	..	..
1	Hydrogen	H	1	1·0081	99·98	1·0081	1·0078
	Deuterium	D	2	2·0147	0·02		
	Triterium	T	3	3·0171	..		
2	Helium	He	3	3·0171	..	4·003	4·002
	Helium	He	4	4·0039	100		
3	Lithium	Li	6	6·0167	7·9	6·9374	6·94
	Lithium	Li	7	7·0180	92·1		
4	Beryllium	Be	8	8·0078	(0·05)	9·0129	9·02
	Beryllium	Be	9	9·0149	99·95		
	Beryllium	Be	10	10·0164	..		
5	Boron	B	10	10·0161	20	10·811	10·82
	Boron	B	11	11·0128	80		
6	Carbon	C	12	12·0036	99·3	12·008	12·01
	Carbon	C	13	13·0073	0·7		
7	Nitrogen	N	14	14·0073	99·62	14·008	14·008
	Nitrogen	N	15	15·0048	0·38		
8	Oxygen	O	16	16·0000	99·8	16·0000	16·0000
	Oxygen	O	17	17·0046	0·03		
	Oxygen	O	18	18·0038	0·16		
9	Fluorine	F	19	19·0049	100	19·000	19·000
10	Neon	Ne	20	19·9986	90·0	20·191	20·183
	Neon	Ne	21	..	0·27		
	Neon	Ne	22	21·9985	9·73		
11	Sodium	Na	23	..	100	..	22·994
12	Magnesium	Mg	24	23·9938	77·4	24·33	24·32
	Magnesium	Mg	25	..	11·5		
	Magnesium	Mg	26	..	11·1		
13	Aluminium	Al	27	26·9911	100	26·985	26·97
14	Silicon	Si	28	27·9860	89·6	28·122	28·06
	Silicon	Si	29	28·9864	6·2		
	Silicon	Si	30	29·9845	4·2		
15	Phosphorus	P	31	30·9844	100	30·978	30·978
16	Sulphur	S	32	31·9812	96	32·05	32·06
	Sulphur	S	33	..	1		
	Sulphur	S	34	33·9799	3		
17	Chlorine	Cl	35	34·9796	76	35·452	35·457
	Chlorine	Cl	37	36·9777	24		
18	Argon	A	36	35·976	0·31	39·953	39·944
	Argon	A	38	37·9753	0·06		
	Argon	A	40	39·9754	99·63		
			Mass-numbers (abundance in %)				
19	Potassium	K	39 (93·4); 40 (0·01); 41 (6·6)			39·096	39·096
20	Calcium	Ca	40 (96·76); 42 (0·77); 43 (0·17); 44 (2·30)			40·076	40·08

TABLE 43 (*cont.*)

	Element	Symbol	Mass-numbers (abundance in %)	Combining weight (oxygen = 16)	
				Calculated from isotopic composition	Determined directly
21	Scandium .	Sc	45 (100)	44·96	45·10
22	Titanium .	Ti	46 (8·5) ; 47 (7·8) ; 48 (71·3) ; 49 (5·5) ; 50 (6·9)	47·91	47·90
23	Vanadium .	V	51	..	50·95
24	Chromium .	Cr	50 (4·9) ; 52 (81·6) ; 53 (10·4) ; 54 (3·1)	52·005	52·01
25	Manganese .	Mn	55	..	54·93
26	Iron . .	Fe	54 (6·5) ; 56 (90·7) ; 57 (2·8)	55·84	55·84
27	Cobalt . .	Co	57 (0·17) ; 59 (99·83)	..	58·94
28	Nickel . .	Ni	58 (67·3) ; 60 (26·9) ; 61 (1) ; 62 (3·8) ; 64 (1)	58·71	58·69
29	Copper . .	Cu	63 (70) ; 65 (30)	..	63·57
30	Zinc . .	Zn	64 (50·4) ; 66 (27·2) ; 67 (4·2) ; 68 (17·8) ; 70 (0·4)	65·33	65·38
31	Gallium . .	Ga	69 (61·5) ; 71 (38·5)	69·71	69·72
32	Germanium .	Ge	70 (21·2) ; 72 (27·3) ; 73 (7·9) ; 74 (37·1) ; 76 (6·5)	72·57	72·60
33	Arsenic . .	As	75 (100)	74·918	74·91
34	Selenium .	Se	74 (0·9) ; 76 (9·5) ; 77 (8·3) ; 78 (24·0) ; 80 (48·0) ; 82 (9·3)	78·95	78·96
35	Bromine .	Br	79 (50·0) ; 81 (50·0)	79·910	79·916
36	Krypton .	Kr	78 (0·42) ; 80 (2·45) ; 82 (11·79) ; 83 (11·79) ; 84 (56·85) ; 86 (16·70)	83·76	83·7
37	Rubidium .	Rb	85 (72·8) ; 87 (27·2)	85·45	85·48
38	Strontium .	Sr	84 (0·5) ; 86 (9·6) ; 87 (7·5) 88 (82·4)	87·62	87·63
39	Yttrium .	Y	89	88·91	88·92
40	Zirconium .	Zr	90 (48) ; 91 (11·5) ; 92 (22) ; 94 (17) ; 96 (1·5)	91·24	91·22
41	Niobium .	Nb	93 (100)	92·90	92·91
42	Molybdenum .	Mo	92 (14·2) ; 94 (10·0) ; 95 (15·5) ; 96 (17·8) ; 97 (9·6) ; 98 (23·0) ; 100 (9·8)	95·95	95·95
44	Ruthenium .	Ru	96 (5) ; 99 (12) ; 100 (14) ; 101 (22) ; 102 (30) ; 104 (17)	101·1	101·7
45	Rhodium .	Rh	103 (100)	102·92	102·91
46	Palladium .	Pd	102 (0·8) ; 104 (9·3) ; 105 (22·6) ; 106 (27·2) ; 108 (26·8) ; 110 (13·5)	106·54	106·7
47	Silver . .	Ag	107 (52·5) ; 109 (47·5)	107·87	107·880
48	Cadmium .	Cd	106 (1·5) ; 108 (1·0) ; 110 (15·6) ; 111 (15·2) ; 112 (22·0) ; 113 (14·7) ; 114 (24·0) ; 116 (6·0)	112·2	112·41
49	Indium . .	In	113 (4·5) ; 115 (95·5)	114·80	114·76

TABLE 43 (*cont.*)

Atomic number	*Element*	*Symbol*	*Mass-numbers*	*Combining weigh (oxygen = 16* *Calculated from isotopic composition*	*Determ dire*
50	Tin	Sn	112 (1·1); 114 (0·8); 115 (0·4); 116 (15·5); 117 (9·1); 118 (22·5); 119 (9·8); 120 (28·5); 122 (5·5); 124 (6·8)	118·70	118·7
51	Antimony	Sb	121 (56); 123 (44)	121·78	121·76
52	Tellurium	Te	122 (2·9); 123 (1·6); 124 (4·5); 125 (6·0); 126 (19·0); 128 (32·8); 130 (33·1)	127·58	127·61
53	Iodine	I	127 (100)	126·904	126·92
54	Xenon	X	124 (0·08); 126 (0·08); 128 (2·30); 129 (27·13); 130 (4·18); 131 (20·67); 132 (26·45); 134 (10·31); 136 (8·79)	131·125	131·3
55	Caesium	Cs	133 (100)	132·90	132·91
56	Barium .	Ba	130 (0·16); 132 (0·02); 134 (1·72); 135 (5·7); 136 (8·5); 137 (10·8); 138 (73·1)	137·35	137·36
57	Lanthanum .	La	139 (100)	138·91	138·92
58	Cerium . .	Ce	140 (89); 142 (11)	140·13	140·13
59	Praseodymium	Pr	141 (100)	140·91	140·92
60	Neodymium .	Nd	142 (25·95); 143 (13·0); 144 (22·6); 145 (9·2); 146 (16·5); 148 (6·8); 150 (5·95) [6]	144·29	144·27
62	Samarium	Sa	144 (3); 147 (17); 148 (14); 149 (15); 150 (5); 152 (26); 154 (20)	150·1	150·43
63	Europium	Eu	151 (50·6); 153 (49·4)	151·90	152·0
64	Gadolinium	Gd	155 (21); 156 (23); 157 (17); 158 (23); 160 (16)	156·9	156·9
65	Terbium	Tb	159 (100)	158·19	159·2
	Dysprosium	Dy	161 (22); 162 (25); 163 (25); 164 (28)	162·5	162·46
67	Holmium	Ho	165 (100)	164·91	163·5
	Erbium .	Er	166 (36); 167 (24); 168 (30); 170 (10)	167·15	167·2
69	Thulium	Tu	169 (100)	168·91	169·4
70	Ytterbium	Yb	171 (9); 172 (24); 173 (17); 174 (38); 176 (12)	173·2	173·04
71	Lutecium	Lu	175 (98·5); 177 (1·5)	174·91	175·0
72	Hafnium	Hf	176 (5); 177 (19); 178 (28); 179 (18); 180 (30)	178·4	178·6
73	Tantalum	Ta	181 (100)	180·89	180·88
74	Tungsten	W	182 (22·6); 183 (17·3); 184 (30·2); 186 (29·9)	183·94	184·0
75	Rhenium	Re	185 (38·2); 187 (61·8)	186·2	186·31

TABLE 43 (*cont.*)

	Element	*Symbol*	*Mass-numbers (abundance in %)*	*Combining weight (oxygen = 16)*	
				Calculated from isotopic composition	*Determined directly*
6	Osmium .	Os	186 (1·0); 187 (0·6); 188 (13·4); 189 (17·4); 190 (25·1); 192 (42·5)	190·30	191·5
7	Iridium . .	Ir	191 (33); 193 (67)	192·3	193·1
8	Platinum .	Pt	192 (0·8); 194 (30·2); 195 (35·3); 196 (26·6) 198 (7·2)	195·13	195·23
9	Gold . .	Au	197 (100)	..	197·2
0	Mercury .	Hg	196 (0·10); 197 (0·01); 198 (9·89); 199 (16·45); 200 (23·77); 201 (13·67); 202 (29·27); 203 (0·006); 204 (6·85)	200·60	200·61
1	Thallium .	Tl	203 (29·4); 205 (70·6)	204·41	204·39
2	Lead . .	Pb	204 (1·15); 206 (24·55); 207 (21·35); 208 (52·95) [7]	207·21	207·21
3	Bismuth .	Bi	209 (100)	..	209·00
0	Thorium .	Th	232 (100)	232·02	232·12
2	Uranium .	U	(234); 235 (0·4); 238 (99·6)	238·02	238·07

in comparable amounts. As an additional rule we can state that the number of isotopes even for elements of even atomic number never exceeds 10, and that the difference in mass between the lightest and the heaviest isotope amounts to no more than 12. For all elements apart from hydrogen and ^{3}He the mass even of the lightest isotope is at least double the value of the atomic number ($M \geqslant 2N$). The excess of the value of the mass above the double value of the atomic number is on the average greater, the greater the value of the atomic weight; thus for mercury the lightest isotope is already by 36 units heavier than $2N$.

If we also include the radioactive elements in our considerations, we can say that all integers from 1 to 238 are made use of by the mass-numbers of one or more types of atom, with the single exception of the number 5, for which no representative is yet known. Indeed, some of the numbers are associated with isotopes of several elements. Thus the main isotopes of argon, calcium, and a weak constituent of potassium all have the mass 40, and the three elements tin, xenon, and tellurium all possess atomic types of mass 124. Such atomic types of different elements which possess the same mass are called 'isobars'. In so far as precisional determinations of the masses of isobars are available, it has been found that they are in very exact agreement (cf. ^{3}T and ^{3}He;

^{10}Be and ^{10}B). Moreover, for any future theory of the structure of t atomic nucleus, the following result found for light atoms will be importance, to wit, those types of atoms whose mass-numbers amou to a multiple of 4 show no excess in atomic weight above integral valu (relative to $^{16}O = 16{\cdot}000$), whereas the intervening atomic nuclei show such an excess in mass, and hence they appear to have a le stable structure.

Finally, it is a particularly surprising fact that the combining weigh of all the elements appear to be natural constants, in spite of the lar number of isotopes of which many of them are composed. (On th point see Chap. XXI, p. 200 et seq.)

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XX

THE SEPARATION OF ISOTOPES

In Chapter XV we have discussed the attempts of chemists to separate from each other certain pairs of radio-elements such as radium and mesothorium, thorium and ionium, or radium D and lead. These constitute the first endeavours made for the purpose of separating isotopes. All of them yielded a negative result, and in consequence they led to the formulation of the idea of isotopy. A much wider field of inquiry was opened up by the establishment of the phenomenon of isotopy for the ordinary elements (see Chap. XIX), because in this case there is no limitation to the amount of material available for experiment, and also no limitation in time to be considered owing to spontaneous disintegration during the application of the experimental method used. In spite of the extraordinarily varied experimental conditions to which they have been subjected during many physical and chemical investigations, not even a partial separation of any of the 'mixed elements' (see p. 199) has been noted. From this it follows that, in general, a separation of ordinary isotopes cannot be an easy matter. Nevertheless, before the discovery of the phenomenon of isotopy, no systematic experiments in this direction had been undertaken. Apart from its theoretical interest, accurate knowledge of the conditions under which isotopes can be separated is also necessary, because of the fact that important constants such as the combining weights or the density of mercury can be influenced in a very disturbing manner by such a separation.

Actually there is an element whose isotopes can be separated so readily that not only are the laboratory methods of separating them relatively simple, but the mixing-ratio of the two isotopes in nature also shows fluctuations. The element in question is hydrogen. The properties of 'heavy hydrogen' or 'deuterium' (atomic weight = 2·0147) differ so strongly from those of the much more abundant ordinary hydrogen (atomic weight = 1·0081) that the two components can be easily separated from each other [1] by fractional distillation of liquid hydrogen, by methods of diffusion and also by the particularly simple and convenient method of the electrolysis of water. In what follows, when we are speaking of the methods of separating isotopes, we shall take no further account of this quite exceptional case, in which the one isotope is twice as heavy as the other.

It should be stated in advance that we can only assume the success of a real separation of isotopes if they were available at the beginning of the experiment as a completely uniform mixture. This condition is always satisfied (see Chap. XXI) for the isotopic types of atoms of the elements which occur in nature, but not for the isotopic radioactive substances. Thus, radiothorium extracted from minerals is always accompanied by thorium, with which it is isotopic; but it can readily be prepared free from thorium by separating its immediate parent element mesothorium from the thorium, and awaiting the growth of fresh radiothorium from the mesothorium. In a similar manner all isotopic radio-elements can be obtained in the separated condition if their parent elements are separable, and their reformation does not demand too long a period of time. But it is clear that in these cases, which are based on the divers parentage of the isotopes, we must not speak of a separation of the isotopes, since the separation only has reference to their parent elements, which are not isotopes. The problem assumes a somewhat different complexion when as a result of the diversity of life of two mixed isotopes, it is possible to obtain one of them in the pure state. This case arises, for instance with the active deposit collected from the atmosphere. At first it contains the two isotopes radium B and thorium B, but after one day practically only thorium B is left, since the radium B has meanwhile decayed almost completely into RaD. For this reason it is hardly correct to speak here of a separation of the isotopes, because one of the isotopes entirely vanishes.

Nevertheless, there are also certain less clear cases in which a separation of mixed radioactive isotopes appears to have been really successfully carried out. Thus it has been observed that the ratio thorium B:thorium C as compared with that of radium B: radium C increases when these four elements are adsorbed simultaneously by iron hydroxide. Either the two isotopic B-products or the likewise isotopic C-products must therefore have been adsorbed in different proportions. If, in spite of this, we cannot here speak of a separation of the isotopes in the true sense, the reason is to be found in the fact that the condition of completely uniform mixing before the commencement of the experiment is not satisfied. The B-products and still more the C-products have a great tendency to go into solution with the properties of colloidal particles, and the amount of the colloidal and the molecularly disperse portions depends on the time during which the solvent medium has been allowed to act. Owing to the different half-value periods, the duration of this action of the solvent is not the same for the thorium and the radium products, and since the adsorption is stronger for colloidal particles than for molecularly disperse ones, the result is a displacement of the concentration ratio.

Correspondingly, one process for the concentration of isotopes pro-ned artificially is based on the fact that these freshly produced atomic topes are in another state of chemical binding than the original material. Thus when an organic substance that contains iodine in combination with carbon is bombarded by neutrons, radioactive isotopes of iodine are produced by the capture of neutrons. In this process, however, the molecular binding is severed and the radioactive iodine atoms are not united with carbon. Because of this, it is possible to obtain the active iodine in a very concentrated form by precipitation of the free iodine with silver, or by shaking up the organic liquid well with water, when all the active iodine ions are concentrated in the water [3]. Also, by electrolysis in the liquid or gaseous phase, we can in this way readily concentrate the active isotopes of iodine [4]. These processes do not constitute a separation of the isotopes in the true sense, since the condition of initially complete uniformity in distribution is not satisfied, and it is just this inhomogeneity that is utilized in practice for the concentration of the isotopes. On the other hand, the method of using radio-elements as indicators (see Chap. XVIII) is based essentially on their inseparability, and it is therefore clear that we must here be very careful to ensure that the process of mixing with the indicator is carried out in the molecularly disperse solution, or in the liquid or the gaseous state.

The first method to achieve a partial separation of isotopes in weighable amounts was that of 'ideal distillation'. It is based on the following consideration:

When a liquid is in equilibrium with its saturated vapour, a definite number of molecules of the vapour strike the surface of the liquid in unit time, and are captured; this number must be equal to the number of molecules that pass from the liquid to the vapour phase in the same time. The velocity of this process of kinetic exchange depends on the mean velocity of the molecules of vapour, and likewise on the velocity of the molecules in the liquid. The lighter (mass m_1) of two isotopes will therefore be in a state of more vigorous exchange than the heavier isotope (mass m_2). Now according to the laws of the kinetic theory the product mv^2 must be constant, so that the velocities will be related inversely as the square roots of the masses. From this it follows that in the unit of time $\sqrt{\dfrac{m_2}{m_1}}$ times as many molecules of the lighter isotope as of the heavier isotope will pass over from the surface into the vapour phase and, conversely, will be condensed from the vapour phase. In the ordinary process of distillation the number of molecules condensed in the distillate is only a small fraction of the number of molecules that take part in the kinetic interchange between the liquid and the vapour in the same time. Thus, although in unit time more molecules of the lighter isotope leave the liquid, this isotope does not become more concentrated in the distillate, since conversely and at the same time more molecules of the lighter isotope condense out from the vapour phase. The average composition of the vapour is the same as that of the liquid. But if we conduct the process along irreversible channels by preventing the molecules which leave the liquid from being returned to it, it is then possible to concentrate the lighter isotope in the distillate. If all the molecules that have left the liquid are held fast before their direction is reversed by collisions with other molecules, then the proportion in which the isotopic molecular types exist in the distillate must be equal to their ratio in the liquid, multiplied by the ratio of their average velocities. It follows that $\frac{c_1}{c_2} = \sqrt{\frac{m_2}{m_1}}$ times as much of the lighter isotope will be condensed as of the heavier isotope. We see, then, that although the *vapour pressures* of two isotopes, except at the lowest temperatures, are indistinguishably identical, it is possible to effect a partial separation by utilizing the fact that their *velocities of vaporization* are different. The degree of separation can be increased by repetition of this process of 'ideal distillation', just as in the case of other fractional distillations.

From what has been said it is clear that various conditions must be fulfilled in order that the method may be a practicable one. In the first place the vapour pressure must be kept so low that the mutual collisions of the molecules can be neglected, as they effect a recoil of the escaping molecules back into the liquid. Furthermore, the surface upon which the vaporized molecules strike must be of such a nature that all the molecules are held by it, and none of them are reflected. This is attained most conveniently by the introduction of a strongly cooled glass surface opposite to the liquid surface. Finally, care must be taken to ensure that the composition of the surface of the liquid does not change relatively to the interior of the liquid; for if the kinetic exchange between the surface and the interior of the liquid does not take place sufficiently rapidly, the escape of the lighter isotope will result in a concentration of the heavier isotope in the surface layers, and this will prevent any further concentration of the lighter isotope in the space above the liquid. This last condition restricts the applicability of this method of separation to liquids, and renders it useless for solid bodies.

The first success achieved by this process of ideal distillation was in the partial separation of the isotopes of mercury. The apparatus used for this purpose is depicted in Fig. 46. 300 c.c. of mercury were introduced into the intervening space between the inner and outer walls of a Dewar vessel, the space being then highly evacuated and the interior of the flask *A* filled with liquid air. The mercury was heated to about 45° C. by means of the oil-bath *C*, so that its vapour pressure was about 0·01 mm. and the amount which vaporized per hour per square centimetre of its surface was about 0·35 c.c. This vaporized mercury froze on the glass wall of the flask *A*. After about one-quarter of the amount of mercury had been condensed in this way, the experiment was interrupted, and the residual heavier mercury was transferred to the evacuated vessel *E* by opening the stopcock *D*, whence it was allowed to flow from the apparatus by way of the stopcock *G*. The next step was the removal of the liquid air from the vessel *A*, so that the mercury that had condensed on it could thaw, after which it was removed from the apparatus in the same way as that used for the removal of the residue from the distillation. By carrying out this process repeatedly it was possible to divide an initial quantity of 2700 c.c. of mercury into a number of fractions, some of which had a greater and some a lesser specific gravity than normal mercury. The heaviest fraction (volume = 0·2 c.c.) had a density of 1·00023 (relative to Hg = 1), and the lightest fraction (likewise 0·2 c.c.) a density of 0·99974, so that the difference in density between the heaviest and the lightest samples of mercury amounted to about 0·05 per cent. For equal volumes the conductivities of the two samples were indistinguishably identical, whereas the combining weights differed by almost 0·1 unit, as was to be expected. The combining weight of the heaviest fraction was 200·632, and that of the lightest fraction 200·564, whereas the combining weight of ordinary mercury is 200·61.

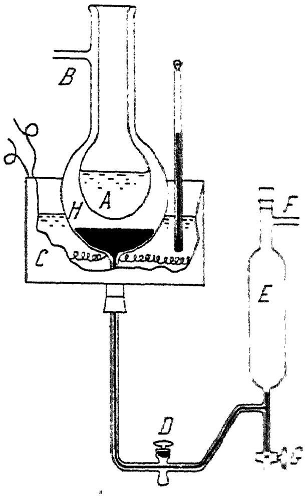

FIG. 46. Apparatus for the Partial Separation of the Isotopes of Mercury.

It has also been possible to effect a partial separation of the isotopes of chlorine by the same process, and using a 7N aqueous solution of HCl for the ideal distillation. The difference in the combining weights of the two chlorine fractions amounted to a little more than two units in the second decimal place, corresponding to a displacement of the mixing ratio of the two isotopes ^{35}Cl and ^{37}Cl of approximately 6 per cent.

A partial separation of the isotopes of zinc has also been carried out in this manner. Experiments performed in an attempt to displace the mixing ratio of the isotopes of potassium were of particular interest, because it was possible from them to draw conclusions as to the isotope responsible for the radioactivity of potassium. By use of the method of ideal distillation for the mixed element potassium, which consists of 93 per cent. of ^{39}K, 7 per cent. of ^{41}K, and 0·01 per cent. of ^{40}K, a heavier fraction was obtained. The radioactivity of this was found to be greater by 4·4 per cent. than that of ordinary potassium, which showed that the radioactivity of potassium is due to a heavier isotopic constituent. Atomic weight determinations of the heavier fraction revealed an increase in the concentration of ^{41}K by as much as 7·3 per cent. [5]. From this it follows that the radioactive isotope is less readily separated than ^{41}K, and that accordingly it must have the mass-number 40.

Experiments on fractional diffusion have been more effective than those of distillation for the separation of isotopes. When a mixture of two isotopes in the vapour or gaseous state is allowed to flow through a narrow opening, the lighter isotope will strike the opening more frequently than the heavier isotope, in consequence of its greater molecular velocity. As a result of this, the probability of the passage of the lighter isotope through the opening will be $\sqrt{\frac{m_2}{m_1}}$ times greater than that of the heavier isotope, where m_1 and m_2 are their respective masses. Now if care be taken to ensure that the molecules are caught on the other side of the opening, and so prevented from streaming back into the vessel, the lighter isotope will be concentrated in the condensed fraction for the ideal case in the ratio $\sqrt{\frac{m_2}{m_1}}$ by this method also.

A certain amount of success was achieved by a method of diffusion with the isotopes of neon as long ago as 1913, at the time of the discovery of the phenomenon of isotopy. Here the concentration was effected by the use of porous clay pipes. More definite results were obtained later by the application of a similar process to mercury, in which the diffusion took place through punctured platinum foils. The method was also applied with some success in the case of chlorine, by allowing HCl to diffuse through clay pipes. But it was not until 1932 that the principle became sufficiently far developed to make it possible to effect almost complete separation of gaseous isotopes in a single operation. The apparatus consists of 24 components of separation, each member consisting of two clay tubes and a mercury condensation pump (cf. Fig. 47, in which only four of the constituent parts are drawn, the dividing line between each being indicated by a dotted line). One-third of the gas that streams through the first clay tube of a separating component is drawn off by the pump of the right-hand neighbouring member, and in this process the lighter isotope is somewhat concentrated in fraction. The gas remaining behind streams through the second ay tube, and a second third of the gas is drawn through its walls by he pump of the separating component under consideration, so that ly the final third passes on to the left-hand component, in which the ame process is repeated. The connexions are so arranged that the hter isotope is progressively concentrated in a continuous stream om left to right through the whole apparatus, whereas the heavier

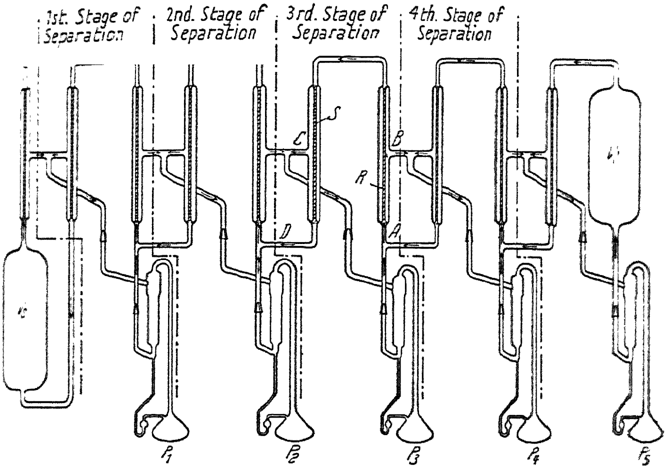

FIG. 47. Apparatus for the Separation of Isotopes by Diffusion.

otope is progressively concentrated in a corresponding manner from ight to left. Details of the connexions and of the disposition of apparatus at the two ends of the series of components can be seen in Fig. 47. The experiments have shown that in the case of neon the apparatus eed only operate for 8 hours in order to obtain a few cubic centimetres f a gaseous mixture in which the isotopes of neon are present in almost qual proportions, whereas the intensity ratio $^{20}Ne:^{22}Ne$ has the value 1 in neon as it occurs in nature. A recently perfected model of the pparatus, consisting of 48 separating components and fitted with pumps, permits of still quicker and more efficient working of the ystem, and has been found especially valuable in the preparation of eavy hydrogen in the pure state [6]. For the purpose of separating the isotopic mixture it is also possible, by means of a special construction of the pumps, to utilize the diffusion of the mixture in the ercury vapour of the pumps, and to dispense with the pipe-clay tubes ntirely.

There are several other methods of separation available which deserve brief mention because of their theoretical interest. Thus the positive-ray method, by means of which isotopes can be recognized by their separation, can also be used under certain circumstances for the preparation of the isotopes in the pure state. When the problem presented itself of examining separately the effect of the bombardment of the individual isotopes of lithium with light and with heavy hydrogen nuclei, films of metallic lithium consisting respectively of only ^{6}Li or ^{7}Li were prepared by resolving the rays from lithium in accordance with the principle used in the mass-spectrograph.

Since isotopes are practically identical in their chemical properties, the most efficient methods used for separating them are based on differences in their masses, and for this reason the processes so far described differ fundamentally from the methods applied for the separation of substances in other branches of chemistry. Nevertheless, in certain circumstances it is possible to effect a separation of isotopes also by normal distillation. On theoretical grounds it is to be expected that isotopes evince sensible differences in their vapour pressures at very low temperatures. If account be taken of zero-point energy, it is found that at low temperatures the lighter isotope must have the higher vapour pressure, whereas if there is no zero-point energy it will have the lesser vapour pressure. When neon is fractionally distilled at a temperature of −248·4° C., neon of unmistakably smaller density than the normal value is obtained in the more volatile portion, whereas a heavier fraction remains in the residue, so that the lighter isotope must have the greater vapour pressure. The significance of this result is primarily that it proves by means of an *experimentum crucis* the necessity for the acceptance of zero-point energy; but for the practical separation of isotopes, of course, this elaborate process can be dispensed with.

On theoretical grounds it is further to be expected that the separability of the hydrogen isotopes does not constitute a completely isolated example of separation by simple chemical and electrochemical processes. For the other light elements there also exists, albeit to a very much smaller degree, the possibility of a separation of their isotopes on the basis of their chemical or electrochemical dissimilarity. Such experiments have been carried out quite recently with lithium, carbon, nitrogen and oxygen. In the case of carbon (isotopes ^{12}C and ^{13}C) use was made of the different reaction velocities of the two types of CO_2 with water; by using an enzyme as catalyser and a complicated counter-current scrubbing apparatus, the content of ^{13}C in one fraction was increased from 1·06 per cent. to 1·36 per cent. [7]. For the separation of the nitrogen isotopes ^{14}N and ^{15}N use was made of the reaction

$$^{15}NH_3+{}^{14}NH_4^+ \rightleftarrows {}^{14}NH_3+{}^{15}NH_4^+.$$

The ratio of ^{14}N to ^{15}N was found to have been reduced from 250 to 234 [8]. The vapour pressures of the ^{16}O and ^{18}O varieties of water are sufficiently different to ensure that, when a fractional distillation is carried out in the above-mentioned fractionation column, a threefold increase in concentration of the heavier isotope can be effected after the lapse of eight days [9]. Finally, by virtue of differences in the electrode potentials of ^{7}Li and ^{6}Li it has been possible to effect a change in their isotopic ratio from 11·6 to 5·1 [10].

In a few specially favourable cases it has been possible to effect a separation of isotopes by photochemical methods. Since carbon and oxygen are practically pure elements, and chlorine consists of the two atomic types ^{35}Cl and ^{37}Cl, it follows that there will be three different kinds of phosgene molecules: $CO^{35}Cl^{35}Cl$, $CO^{35}Cl^{37}Cl$, and $CO^{37}Cl^{37}Cl$. In the absorption spectrum different lines will correspond to these three types of molecules. For a certain triplet the component line of shortest wave-length has the value 2,816·179 A. and is due to the molecule $CO^{35}Cl^{35}Cl$. It is possible to produce light of exactly the same wave-length by removing all other wave-lengths from the spectrum of a spark between aluminium electrodes by means of light filters. As is well known, only molecules that absorb light are broken down photochemically, so that a decomposing action of this filtered light is to be expected only for this one kind of molecule. By raying the phosgene mixture in this way, it was in fact found that chlorine was liberated, and its combining weight was 35·429 instead of the normal value 35·457. It was thus shown that the filtered light had decomposed mainly those molecules that contained two chlorine atoms of mass 35. It was not to be expected that the action would be restricted exclusively to this type of molecule, since, in addition to the lines, the absorption spectrum shows also a continuous background. A similar partial separation of isotopes has also been carried out by the illumination of mercury vapour with filtered light [11]; mainly the excited isotopes were oxidized, and so removed from the gaseous phase.

On the basis of theoretical considerations various other methods have also been tried out, but they have not yet led to successful results. Thus in many cases the method of diffusion in aqueous solutions has been applied, as in attempts to separate the two isotopes of uranium. But for diffusion in liquids the advantage of greater molecular velocity possessed by the lighter isotope is compensated by the numerous collisions with the molecules of the liquid, by virtue of which the lighter isotope more readily loses its direction. Moreover, in aqueous solution the difference in the masses and hence also in the mobilities of the isotopic particles can be substantially diminished by the effect of hydration. An appreciable relative speeding up of the particles of the lighter isotope has in fact never been observed. The same thing holds for the mobility of the ions in solutions.

A spontaneous separation of the isotopes might be expected in the case of the mixed elements occurring in nature as a consequence of the effect of the gravitational field of the earth. The lighter gases in the atmosphere might be expected to become concentrated relatively to the heavier ones at higher levels, and it might likewise be assumed that at great heights the ratio of the two neon isotopes would be displaced in favour of the lighter isotope; thus at a height of 10 km., instead of 91 per cent. ^{20}Ne and 9 per cent. ^{22}Ne, there should be present 92 per cent. ^{20}Ne and only 8 per cent. ^{22}Ne. But such a displacement of the molecular composition of the atmosphere is only to be expected if we suppose that the distribution of the molecules in the gravitational field can take place strictly in accordance with the laws of diffusion, and without disturbance by convection currents. These last, however, really exert a preponderating influence within the atmosphere. Similar considerations hold validity for the dependence of the isotopic ratio on depth in the case of mixed elements from the ocean depths. NaCl from the deepest region of the ocean, about 10 km., should be by so much richer in ^{37}Cl than in ^{35}Cl that the combining weight of the chlorine contained in it should have the value 35·6 instead of 35·46. But here, also, the disturbance of the gravitational distribution by ocean currents is so strong that it has not been possible to detect the effect even qualitatively.

In principle, the same effects as are produced by gravitational forces should also be attainable by centrifugal forces. For the earth a rotational velocity of 1 km./sec. corresponds to a difference in height of about 40 km. It has not yet been possible to construct centrifuges of such efficiency, and at the same time so completely to exclude disturbances likely to arise from convection, as to render practicable a separation of isotopes by this means.

In view of the great difficulties with which the separation of isotopes taxes the equipment even of a modern laboratory, it is hardly to be expected that any natural chemical processes whatsoever, that take place on this planet, will be able to bring about an appreciable displacement of the isotopic ratio of an element, always excepting, of course, the case of hydrogen. In complete accord with this is the fact mentioned elsewhere (pp. 186, and 200–202), that the combining weights of the chemical elements are natural constants. Biological processes also appear to be ineffective in bringing about a separation of isotopes. Thus the isotopic composition of the element copper, extracted from the blood of the horseshoe crab (*limbus polyphemus*), has been the subject of careful examination, but the copper so obtained was found to have the same combining weight as ordinary copper [12].

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XXI

MIXED ELEMENTS AND PURE ELEMENTS. COMBINING WEIGHTS AND ATOMIC WEIGHTS

As we have seen in Chapter XIX, Dalton's hypothesis, that a chemical element consists only of one quite definite type of atom, has validity only for very few elements. Even with these, e.g. helium, it is very well possible that more sensitive methods will reveal the existence of isotopes (cf. Tables 43 and 56). In the case of the majority of the elements it is already known that they are composed of several isotopic types of atoms. As a result of the chemical inseparability of various radioactive substances (see p. 148) it became clear for the first time that the impossibility of resolving a substance chemically may not constitute proof that its atoms are all of one type, and this conjecture has been completely confirmed by investigations with positive rays. In this way our theoretical ideas on the nature of a chemical element have been strongly modified, since for over a hundred years one had regarded as certain the foundations of atomistics due to Dalton, according to which the number of kinds of atoms was equal to the number of the chemical elements. But the practical significance of this new knowledge is very small for the subject of chemistry, as is shown by the fact that the complex nature possessed by so many elements was so long overlooked by chemists, and was first disclosed by researches so far removed from chemistry as the investigations on positive rays. Hence it is that the regularities in chemistry embodied in the periodic classification must continue to be built up on the conception of the chemical element.

We have already had occasion to discuss the fluctuations in the combining weight of lead obtained from different sources (see p. 15 From the chemical viewpoint, however, these kinds of lead, in which the isotopic atom types are mixed in various proportions, are unitary elements. Their purification and the determination of their 'atomic weight' could be carried out by the usual methods. Such an element consisting of several isotopes is termed a 'mixed element'—an expression we have already used—and it is preferable to speak of its 'combining weight' rather than of its atomic weight, since in the case of chlorine, for example, the relative weights of the atoms contained in it are 35 and 37, whereas its combining weight is 35·457. An element that consists of only one type of atoms is called a 'pure element', and it is associated with a constant atomic weight which indicates directly the weight of its atoms relative to oxygen = 16·0000. When we speak generally of a 'chemical element', it is not clear whether we are dealing with a pure element, or with a mixed element such as lead or chlorine

In view of present-day knowledge we can no longer simply say that the chemical elements cannot be further resolved; it is possible to separate the various types of atoms present in them, and thus to resolve them into substances of different kinds. To-day we may define an element conveniently in the following way: *A chemical element is a substance which is not resolved into simpler substances by the usual chemical processes.* The fact that the elements are not resolved chemically retains its validity for all practical purposes, and here we have the reason why these substances which persist in all chemical reactions rightly bear the name of chemical 'elements'. For other than chemical experiments the same substances do not represent something that cannot be resolved. By means of certain artifices we can bring about a separation of the isotopic atom types (see Chap. XX), and by others a disruption of the atoms (see Chap. X); but since neither of these processes falls within the ambit of normal chemical operations, this compositeness of the elements, which is present in a dual sense, can be neglected in the whole of the vast field of practical chemistry. For practical and didactic purposes the above definition is in general sufficiently precise, since almost all the successful methods of separating isotopes are typically mechanical ones, inasmuch as in them we make use of differences in mass and not of a difference in their chemical properties. Nevertheless, it has been possible to attain by photochemical means and by exchange reactions a partial separation of the isotopes of a few light elements. Moreover, for the isotopic atom types of hydrogen the difference of their chemical properties also is so great that we should certainly have been tempted to consider them as two different chemical elements, had it not been for the fact that the almost complete identity of the chemical properties of the isotopes of all the rest of the elements has led us to regard the nuclear charge as the primary characteristic of an element.

This more exact and more fundamental definition, even though it is more remote from the original chemical meaning of the element concept, can be formulated in the following way:

A chemical element is a substance of which all the atoms have the same nuclear charge. Examples: helium (nuclear charge 2), chlorine (nuclear charge 17), lead from an arbitrary mineral (nuclear charge 82), lead from disintegrated radon (nuclear charge 82).

A pure element is an element that consists of only one type of atom. Examples: helium (atoms of mass 4·002), lead from radon (atoms of RaD, which emits β-rays, of mass 210).

A mixed element is an element that consists of several types of atoms. Examples: chlorine (atoms of mass 35 and 37), lead from galena (atoms of mass 204, 206, 207, and 208).

In the thermodynamic sense a pure element is thus a unitary substance, whereas a mixed element is not. But since we consider both mixed elements and pure elements as chemical elements, we see that the necessity of retaining the systematics of chemistry in spite of the discovery of isotopy has compelled us to free the concept of the chemical element from the thermodynamic concept of matter. The members of the periodic classification of the elements are chemically unresolvable, but in general they are not thermodynamically unitary substances.

In the domain of the radio-elements, for which the isotopic atom types occur separately in nature, in contrast to the ordinary elements, it is usual to enter the most long-lived type in the periodic classification, for with it the chemical properties can be observed most readily; e.g. thorium is taken as element 90, and not, say, uranium X_1 (cf. Tables 40 and 41 with Table 38). Only occasionally, and for special purposes, do we enter all the types of the radio-elements also in the tables of the periodic classification.

The question as to whether a chemical element is a pure or a mixed element is of no practical importance to the chemist, and he is also interested more in the combining weight than in the weight of the individual atom types of an element. Thus, although for scientific purposes a complete table of the 'atom types' is important, the old-time table of the 'chemical elements' and of their 'combining weights' has not lost its significance. Since we have tabulated the atom types of the radio-elements already in Table 38, p. 152, and the atom types of the inactive elements so far as they are at present known in Table 42, p. 182, there only remains to be given here one embodying the chemical elements and their combining weights (Table 44). The arrangement is the one usual in chemistry, the elements being entered in the alphabetical order of their symbols. We have also given the atomic number of each of the elements after its combining weight; with the help of this number we can immediately find the position of the particular element in the periodic classification (see Tables 40 and 41), as well as its atomic composition (see Table 43).

Since the combining weights of the mixed elements are only average values obtained from the weights and the proportions of the isotopic atomic types contained in them, the question arises as to whether they can still be regarded as natural constants. It appears that we can without reservation answer this question in the affirmative, so long as we confine ourselves to the ordinary inactive elements. For these it has not been possible hitherto to establish with certainty fluctuations in their combining weights, even when material from quite different sources has been investigated, with one solitary exception. This is hydrogen, for which a displacement of the mixing ratio of the isotopic

TABLE 44

Combining Weights and Atomic Numbers of the Chemical Elements

ymbol	*Name of element*	*Combining weight*	*Atomic number*	*Symbol*	*Name of element*	*Combining weight*	*Atomi numbe*
Ag	Silver .	107·880	47	N	Nitrogen .	14·008	7
Al	Aluminium	26·97	13	Na	Sodium .	22·994	11
Ar	Argon .	39·944	18	Nb	Niobium .	92·91	41
As	Arsenic .	74·91	33	Nd	Neodymium .	144·27	60
Au	Gold. .	197·2	79	Ne	Neon . .	20·183	10
B	Boron .	10·82	5	Ni	Nickel . .	58·69	28
Ba	Barium .	137·36	56	O	Oxygen .	16·0000	8
Be	Beryllium .	9·02	4	Os	Osmium .	191·5	76
Bi	Bismuth .	209·00	83	P	Phosphorus .	30·978	15
Br	Bromine .	79·916	35	Pb	Lead . .	207·21	82
C	Carbon .	12·01	6	Pd	Palladium .	106·7	46
Ca	Calcium .	40·08	20	Pr	Praseodymium	140·92	59
Cd	Cadmium .	112·41	48	Pt	Platinum .	195·23	78
Ce	Cerium .	140·13	58	Ra	Radium .	226·05	88
Cl	Chlorine .	35·457	17	Rb	Rubidium .	85·48	37
Co	Cobalt .	58·94	27	Re	Rhenium .	186·31	75
Cr	Chromium.	52·01	24	Rh	Rhodium .	102·91	45
Cs	Caesium .	132·91	55	Rn	Radon .	222	86
Cu	Copper .	63·57	29	Ru	Ruthenium .	101·7	44
Dy	Dysprosium	162·46	66	S	Sulphur .	32·06	16
Er	Erbium .	167·2	68	Sb	Antimony .	121·76	51
Eu	Europium .	152·0	63	Sc	Scandium .	45·10	21
F	Fluorine .	19·00	9	Se	Selenium .	78·96	34
Fe	Iron . .	55·84	26	Si	Silicon . .	28·06	14
Ga	Gallium .	69·72	31	Sm	Samarium .	150·43	62
Gd	Gadolinium	156·9	64	Sn	Tin . .	118·70	50
Ge	Germanium	72·60	32	Sr	Strontium .	87·63	38
H	Hydrogen .	1·0078	1	Ta	Tantalum .	180·88	73
He	Helium .	4·002	2	Tb	Terbium .	159·2	65
Hf	Hafnium .	178·6	72	Te	Tellurium .	127·61	52
Hg	Mercury .	200·61	80	Th	Thorium .	232·12	90
Ho	Holmium .	163·5	67	Ti	Titanium .	47·90	22
In	Indium .	114·76	49	Tl	Thallium .	204·39	81
I	Iodine .	126·92	53	Tu	Thulium .	169·4	69
Ir	Iridium .	193·1	77	U	Uranium .	238·07	92
K	Potassium.	39·096	19	V	Vanadium .	50·95	23
Kr	Krypton .	83·7	36	W	Tungsten .	184·0	74
La	Lanthanum	138·92	57	X	Xenon . .	131·3	54
Li	Lithium .	6·940	3	Y	Yttrium .	88·92	39
Lu	Lutecium .	175·0	71	Yb	Ytterbium .	173·04	70
Mg	Magnesium	24·32	12	Zn	Zinc . .	65·38	30
Mn	Manganese	54·93	25	Zr	Zirconium .	91·22	40
Mo	Molybdenum	95·95	42				

takes place much more readily than for the other elements. For example, water from the Dead Sea or from the leaves of a tree contains a little more of the heavy variety of water than does rain-water. But copper and chlorine from widely separated sources of origin, iron, nickel, silicon, and chlorine from terrestrial minerals and from meteorites, mercury from minerals of very different geological age and geographical occurrence, all of these showed complete constancy in the combining weights within the limits of experimental error (cf. Chap. XIX, where this question has already been mentioned). The ratio of the isotopes ^{16}O and ^{18}O in stone meteorites is the same as in terrestrial oxygen; this was shown by determinations of the specific gravity of water made from these sources of oxygen, and by means of mass-spectrograms [1]. From these facts we must conclude that the atomic types of the elements were already formed and had had opportunity for complete mixing before the solidification of the planets. This conclusion is in best agreement with the assumption, which for other reasons seems probable, that our solar system was initially in a fluid magma or gaseous state.

But in the framework of these ideas we must expect that the constancy in the combining weight will be absent when a new formation of atom types has taken place since the solidification of the earth's crust. This case has arisen exclusively with the radio-elements. The lead which has been formed in uranium minerals during the course of geological time has had little or no opportunity of mixing with ordinary lead, and in accordance with this we find here those fluctuations in the combining weight which we have discussed in Chapter XV. An analogous case is the low combining weight of strontium formed by the disintegration of rubidium (see p. 237). The deviations in the cases of lead, thorium, and strontium of radioactive origin are, together with those achieved for a number of elements by an artificial separation of the isotopes (see Chap. XX, p. 187), the only fluctuations that it has been possible so far to establish. In all other cases—always with the exception of hydrogen—with the present-day attainable accuracy, the combining weights of the chemical elements are natural constants which have not lost any of their practical importance as a result of the recognition of the complex nature of the mixed elements.

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XXII

THE PREPARATION OF RADIOACTIVE SUBSTANCES

It will be clear from what has already been said about the chemical nature of radioactive substances that they do not constitute a group of elements with the same, or even with similar chemical properties. Their physical behaviour, the disintegration of their atoms, is the only thing they have in common. From the chemical point of view they differ greatly from one another, and this applies even to elements such as radium and radon which are very closely related genetically. For this reason, then, no single process can be applied to the production of one and all of them, and it is not possible to state certain group reactions as, say, in the case of the rare earths or the alkali metals.

Moreover, owing to their radioactivity and consequent instability, we are here faced with special difficulties such as we meet in no other branch of chemistry. An inactive substance that has once been freed from foreign chemical elements remains permanently pure, provided it is suitably stored. It would strike a chemist as being very remarkable if chemical elements that he had carefully removed were to reappear after the lapse of a few hours or weeks. But with radioactive substances this is always occurring, with some more quickly than with others. Of course, when the substance is regenerated after an interval of a few hours or a few minutes, the amounts formed in this time are never weighable nor visible, but are only rendered evident by the radiation they emit. In the ordinary chemical sense the preparations have remained pure, and it is impossible to recognize the admixture of a foreign element either by means of reagents or with the aid of a spectroscope. Nevertheless, the electroscope reveals to us that the substance which had been removed is again present in the material.

In the preparation of radioactive substances in a state of purity it is therefore necessary to differentiate between the terms 'chemically pure' and 'radioactively pure'. The methods we apply will differ greatly according to the purpose we have in hand. 'Chemically pure' thorium, to take one example, may contain several radioactive disintegration products as impurities without its utility being adversely affected. Conversely, a preparation of radium which is pure from the radioactive viewpoint (e.g. free from mesothorium) may, for many radiological investigations, contain quite appreciable amounts of barium. In the *chemical* sense we can obtain only very few of the radioactive substances in the pure state; besides uranium and thorium, only protoactinium, radium, radon, and radium D can be obtained in visible quantities. Nevertheless, we are rarely concerned with the chemical purity of these substances, for their most valuable feature is their radioactive properties, which lose little or none of their effectiveness by the admixture of inactive material. Thus chemically pure radium chloride (i.e. 100 per cent. $RaCl_2$) has so far only been prepared on three occasions (in Paris, in Vienna, and in Munich), and for scientific purposes. We also rarely require complete purity in the radioactive sense, for an 'impurity', especially of the disintegration products of the substance itself, is quite welcome in practice, because in this way the activity of the substance (e.g. mesothorium or radiothorium) increases. In scientific investigations, however, the radiochemist is frequently confronted with the task of preparing the pure substance. But it will be clear from what has been said that in this case he must be informed exactly as to the day and hour at which the 'radioactively pure' preparation is desired, and he will then so arrange his work that the short-lived and hence quickly regenerated disintegration products are removed immediately before the preparation is to be used.

A second difficulty met with in the preparation of pure radioactive substances lies in the fact that many, in fact most, of the radioactive substances cannot be separated chemically from other partly active and partly inactive substances, once they have been mixed, either during their preparation or in consequence of their occurrence together in nature. This difficulty is a much more disagreeable one, because it is capable of making impossible the practical utilization of the radioactive substances. These disturbing elements are isotopes of the substance concerned (see Chap. XV). Radium D, for example, in spite of the relatively large quantity of it which occurs in minerals, and although its chemical properties are quite accurately known, cannot be obtained in concentrated form, in which form it would be very useful for many purposes, because its chemical properties are identical with those of the other types of lead with which it is associated in minerals. We now know that the phenomenon of isotopy is one which also occurs with numerous inactive elements, but in this case the problem of the separation of the isotopes manifests itself in quite another form. Here we require to separate the old chemical elements into fractions differing from each other solely in atomic weight, the solution of which task is sought mainly because of its theoretical importance. But with the radio-elements the individual atomic types of the elements are characterized by especially interesting and valuable properties, their radiations, and hence the problem of the separation of isotopes appears here as the preparation in the 'pure state' of the radioactive substance concerned.

A final difficulty met with in the isolation of the radio-elements has its origin in the short life of some of them. When they decay in fractions of a second, it is clear that we cannot obtain them chemical manipulations such as precipitation, filtration, and so on: but even those which live for several minutes or hours cannot generally be isolated chemically from such a complicated mixture as that presented by most uranium and thorium minerals. This difficulty can be avoided, however, for the quicker an element decays the more rapidly it will be regenerated from its parent substance. Correspondingly, the general principle involved in the preparation of short-lived substances consists in separating the parent substance from the mineral in as concentrated a form as possible. Should this parent substance also be unstable, we should separate an earlier more stable member of the disintegration series. We can then await the growth of the desired product, and undertake the chemical separation in a manner which is generally both easy and quick. Table 45 gives a summary of the radio-elements which, in consequence of their long half-value periods (T), entered in the table, can be extracted directly from the minerals. They are arranged in the table in the order of decreasing half-value period, and the last five can also be obtained from their parent substances, just as in the case of the typically 'short-lived' elements. Under favourable circumstances this is a particularly easy process with RaD, for one of its more distant ancestors, radon, is easily prepared in the pure state, and the intermediate products are all short-lived.

TABLE 45

Radio-elements of Long Life which can be extracted directly from Minerals

Thorium . .	$T = 1{\cdot}34\times10^{10}$ years	Radium D† . .	$T =$ 22 years
Uranium . .	$4{\cdot}4\times10^{9}$ years	Actinium . . .	13·5 years
Ionium† . .	$8{\cdot}3\times10^{4}$ years	Mesothorium 1† . .	6·7 years
Protoactinium .	$3{\cdot}2\times10^{4}$ years	Radiothorium† . .	1·9 years
Radium . .	1,590 years	Polonium . . .	140 days

Those elements denoted by † cannot be extracted directly as pure elements owing to the fact that the minerals contain isotopes of longer life.

In what follows we shall give separate accounts of the most important facts concerning the preparation of the long-lived and of the short-lived radio-elements.

A. PREPARATION OF THE RADIO-ELEMENTS OF LONG LIFE

Thorium. Since large quantities of very pure thorium are required in industry, quite a number of processes for the extraction of 'chemically pure' thorium are known. But we shall not deal with them here, because fuller information can be obtained from text-books on chemistry and particularly from special works on the rare earths. It should be mentioned here, however, that the thorium derived by the usual processes is never 'radioactively pure', but is contaminated at least by its isotope radiothorium. Nevertheless, there is a means of separating thorium even from this radio-element, and we propose to give it, since it is instructive to see how the chemist, by taking time into his consideration can carry out purifications that would be impossible by direct means. The radiothorium contained in thorium after its chemical purification decays to a negligible fraction of its former value after the lapse of 20 years; but during this time mesothorium 1 is formed from the thorium, and from this fresh radiothorium is produced. By adding barium to the solution and separating the thorium from it, we can, by frequent repetition of this process throughout the twenty years, ensure that appreciable quantities of mesothorium can never accumulate in the thorium solution. During this period the old radiothorium has completely disappeared and no fresh radiothorium has been regenerated in the solution, so that we now have not only the chemically pure thorium salt in solution, but it is also pure from the radioactive point of view. In order that this may be successful, however, it is necessary that the thorium mineral should contain only very small amounts of uranium, so that the separated thorium will be contaminated with the merest traces of the long-lived isotope ionium.

Monazite sand is used almost exclusively as the source for the extraction of thorium. The best-known thorium minerals are thorite and thorianite (see also Table 52, p. 273).

Uranium. We do not propose to deal with the question of the preparation of chemically pure uranium salts either, as the necessary instructions are readily found in the literature of chemistry. In contrast to thorium, we cannot obtain uranium as a 'pure element' no matter what artifice we may adopt. Since actino-uranium and uranium II, which are isotopic with uranium I ($T = 4{\cdot}4\times10^9$ years), possess large half-value periods, $T = 7\times10^8$ and 3×10^5 years respectively, it is impossible to wait till they have decayed. But for all practical purposes (i.e. as regards the magnitude of its combining weight, etc.) the 'mixed element' uranium consists only of uranium I; the amount of AcU is less than 1 per cent., and that of U_{II} less than one-hundredth per cent of the amount of U_I.

Pitchblende is the chief mineral now used in the manufacture of uranium (see Table 52, p. 273).

Radium. In all unaltered primary uranium minerals about $3{\cdot}4\times10^{-7}$ gm. of radium is associated with 1 gm. of uranium. Correspondingly we find only about 2 gm. of radium in 10,000 kg. of a uranium pitchblende. Its extraction is a very tedious task, of course, but it is not disturbed by the presence of any isotope of radium, and it is due to this happy circumstance that the first attempt to extract radium from pitchblende residues was crowned with complete success. This work was carried out by M. and Mme Pierre Curie. Since the chemical properties radium are very closely related to those of barium, we can apply process which permits a quantitative and rapid separation of barium from the remaining constituents of the mineral. It is not possible to give definite and generally valid procedure for the extraction of radium, because the initial materials require different kinds of treatment. Moreover, the price of radium is not high enough to justify the rejection of the other valuable constituents of the minerals, without endangering the business aspect of the process. Thus the uranium content is about one-third as valuable as the radium content, and when vanadium is present must always be extracted. Nevertheless, in all the processes, we can differentiate roughly between the following main stages in the extraction:

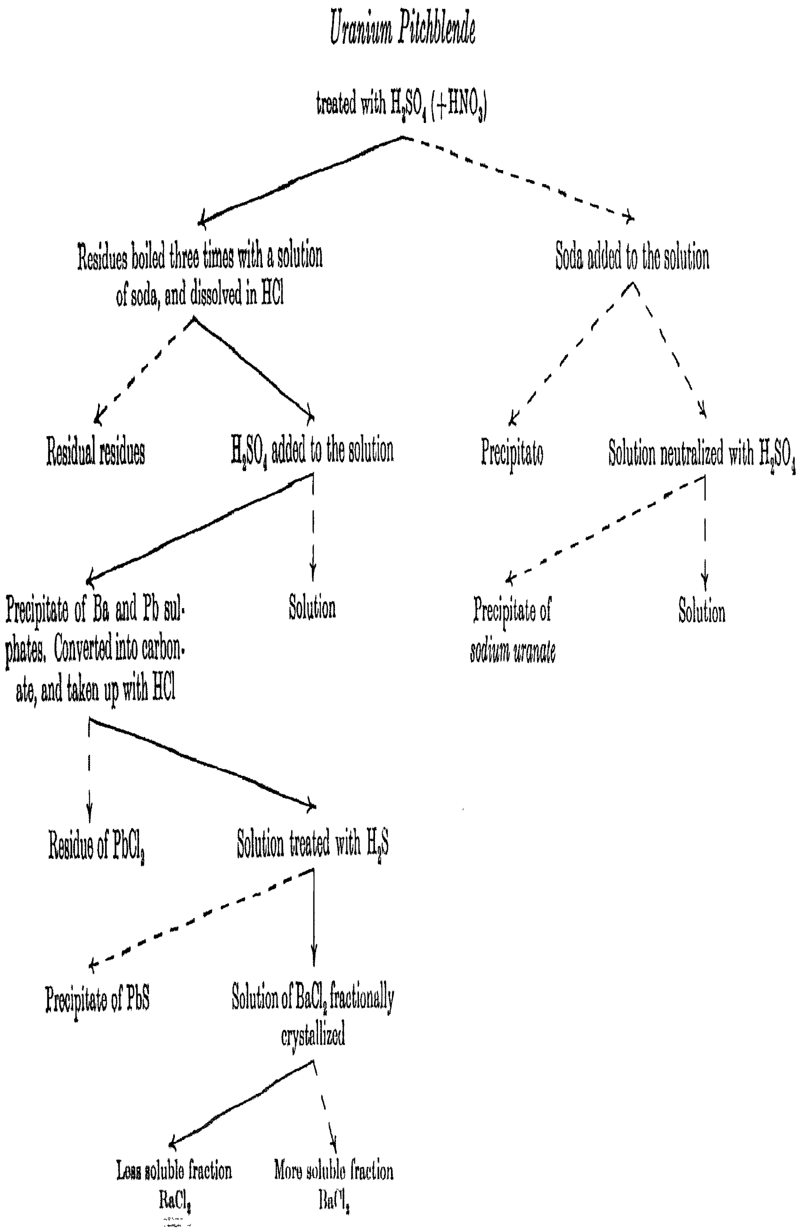
1. Solution or opening up of the uranium minerals.
2. Separation of all sulphates insoluble in water.
3. Their conversion into soluble salts.
4. Purification of the radium and barium from foreign constituents.
5. Fractional enrichment of the radium in the barium.

Each of these points can be widely varied, and we do not propose to enter into the numerous suggestions and experiments on this aspect of the subject. We shall content ourselves with the discussion of the main features of two processes that have been well tried on a large scale, and which differ greatly both in the initial materials used and in the methods adopted for their treatment.

Process in Use at St. Joachimstal (Jáchymòv)

St. Joachimstal in the Erzgebirge is the most important source of radium-bearing ores in Europe. Here the process described below has been applied continuously since 1910, originally under the control of the Austrian Government, and since the mines and factory were taken over by the Czechoslovak authorities, nothing has been altered in the methods originally introduced.

The initial material is uranium pitchblende, the main constituent of which is U_3O_8, with admixture of very many other compounds, especially PbS, SiO_2, CaO, FeO, and MgO. It contains crystalline material in a highly dispersed state, the size of the individual crystals being only 10^{-4} to 10^{-7} cm. The broken-up ore is treated with sulphuric acid to which some nitric acid has been added, the concentration being such that the uranium goes completely into solution, whereas the radium remains behind quantitatively with the insoluble sulphates of calcium, barium, and lead. These are more or less completely taken up by boiling three times with a solution of soda, the parts which still remain unchanged, the so-called ‘residual residues’, containing among other things the whole of the tantalum, and to these we shall return in


Uranium Pitchblende
treated with H_2SO_4 $(+HNO_3)$
Residues boiled three times with a solution of soda, and dissolved in HCl
Soda added to the solution
Residual residues
H_2SO_4 added to the solution
Precipitate
Solution neutralized with H_2SO_4
Precipitate of Ba and Pb sulphates. Converted into carbonate, and taken up with HCl
Solution
Precipitate of sodium uranate
Solution
Residue of $PbCl_2$
Solution treated with H_2S
Precipitate of PbS
Solution of $BaCl_2$ fractionally crystallized
Less soluble fraction $RaCl_2$
More soluble fraction $BaCl_2$

connexion with the extraction of protoactinium. For the purpose of purification the dissolved constituents are again precipitated as sulphate, converted into carbonates and then into chlorides. In the process the lead remains partly undissolved as chloride, and it is partly removed by means of precipitation with sulphuretted hydrogen. The final part of the process is the fractional crystallization of the mixture of radium and barium chlorides until the required concentration of the radium has been attained. Owing to its smaller solubility, the radium is concentrated in the crystals.

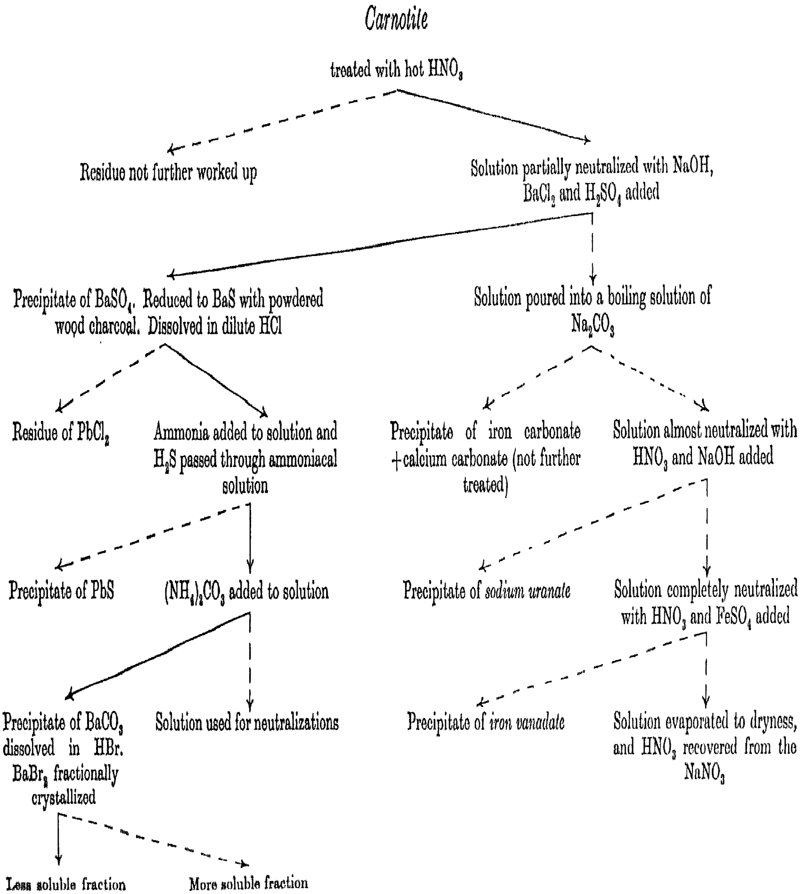
In order to make the various steps in the process of extraction as clear as possible a schematic representation of the process is given on p. 208.

The quantity of radium produced per annum at St. Joachimstal only amounts to 3 or 4 gm., owing to the difficulties to be overcome in the mining of the uranium ore. During recent years a radium factory has been worked at Oolen (near Antwerp) in Belgium, and the annual production of radium is here very much greater than that of St. Joachimstal. The mineral used in the production of radium in the Belgian factory is a rich pitchblende which occurs at Katanga in the Belgian Congo. As the initial material is pitchblende, the essential features of the method of treating the mineral will not differ from those in use at Joachimstal, but details of the process have never been published. The yearly production of radium in Belgium at present amounts to about 36 gm.

b. *Process in Use at Denver*

As a second illustration of the rational extraction of radium, we shall now describe the process developed in the years 1914 and 1915 at Denver in the State of Colorado, North America. The deviations from the Austrian process are due mainly to the fact that the initial material is carnotite, a vanadate of potassium and uranium of composition $K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 2H_2O$, but also partly to the fact that the resources available for the equipment of the plant were much greater than in the previous case.

The ore is treated with hot concentrated nitric acid to which a small amount of hydrochloric acid has been added, and the whole of the radium is thereby brought into solution, in spite of the presence of sulphates. After partial neutralization with NaOH and addition of barium, it is then precipitated as sulphate together with barium and lead. The decanted solution is worked up for uranium and vanadium, whilst the sulphates obtained are mixed with wood charcoal in a graphite crucible, heated for 7 hours at 800° C., and so converted into sulphides. These are dissolved in hydrochloric acid, the lead is removed by precipitation with hydrogen sulphide in ammoniacal solution, whereas the



Carnotite

treated with hot HNO_3

Residue not further worked up

Solution partially neutralized with NaOH, $BaCl_2$ and H_2SO_4 added

Precipitate of $BaSO_4$. Reduced to BaS with powdered wood charcoal. Dissolved in dilute HCl

Solution poured into a boiling solution of Na_2CO_3

Residue of $PbCl_2$

Ammonia added to solution and H_2S passed through ammoniacal solution

Precipitate of iron carbonate + calcium carbonate (not further treated)

Solution almost neutralized with HNO_3 and NaOH added

Precipitate of PbS

$(NH_4)_2CO_3$ added to solution

Precipitate of *sodium uranate*

Solution completely neutralized with HNO_3 and $FeSO_4$ added

Precipitate of $BaCO_3$ dissolved in HBr. $BaBr_2$ fractionally crystallized

Solution used for neutralizations

Precipitate of *iron vanadate*

Solution evaporated to dryness, and HNO_3 recovered from the $NaNO_3$

Less soluble fraction $BaBr_2$

More soluble fraction $BaBr_2$

barium and radium are precipitated as carbonates, and again dissolved in hydrobromic acid. In this case the enrichment of the radium in the barium is carried out by fractional crystallization of the bromides.

The Denver process is represented schematically on p. 210, the operations leading to the extraction of uranium and vanadium being included also. The American carnotites contain on the average 4 mg. radium per metric ton. Up to the end of 1922 about 52,000 tons of the ore had been worked up, corresponding to the production of about 200 gm. of radium. Since the opening of the Belgian factory (see above) both the American and Joachimstal productions of radium have lost in importance year by year, and from time to time the factories have been closed down entirely. At the same time the price of radium has gone down (see p. 224).

The virtual monopoly held by the Belgian producers of radium for more than a decade has recently come to an end. In 1930 an extensive occurrence of pitchblende was discovered on the eastern shores of the Great Bear Lake, North West Territory, Canada [1]. This pitchblende resembles the Joachimstal deposits in its general character and in the nature of the metallic minerals associated with it. Picked samples of the ore contain from 45 to 55 per cent. of U_3O_8, and the thorium content of the ore is almost negligible (*c.* 0·004 per cent.). Lead extracted from it is found to be fairly pure RaG, for the combining weight of this lead is 206·06, and the mineral contains round 10 per cent. of lead. As the most northerly point reached by the railway system is over 1,000 miles distant from the Great Bear Lake, the transport of the material has presented very great difficulties. These have been surmounted by the conveyance of the concentrated ores by boat during the short period when rivers and lakes are not ice-bound, and during the rest of the year they are transported by air to the nearest railway terminus. A radium refinery has been erected at Port Hope, Ontario, and already 3 gm. of radium are being produced monthly. It is hoped that the output will soon be doubled. The undertaking is working smoothly, and in all probability it will effect a further reduction in the international price of radium (see p. 224). Finally, it may be mentioned that, during the past few years, the Chemical Works at Treibach in Carinthia (Austria), working on ores from various sources, have been able to produce several grams of radium annually.

From the discovery of radium to the end of 1936 it is estimated [2] that the amounts of radium produced from ores derived from various sources are as follows:

St. Joachimstal (Jáchymòv) .	50 gm.	Canada (Great Bear Lake) .	28 gm.
United States of America .	250 ,,	Portugal, Russia, England, etc.	50 ,,
Belgian Congo (Katanga) .	500 ,,	World production = *c.* 900 gm.	

Mesothorium 1. We shall proceed immediately to the description of the extraction of mesothorium, because this element is isotopic with radium, and hence the extraction of the two substances is carried out by very similar processes. Mesothorium is found in every thorium mineral, there being $3{\cdot}7 \times 10^{-10}$ gm. present with each gram of thorium. But since all thorium minerals also contain a small quantity of uranium, and 1 gm. of uranium corresponds to the presence of $3{\cdot}4 \times 10^{-7}$ gm. of radium, it follows that all mesothorium extracted from minerals must be mixed with an appreciable quantity by weight of radium, even though the radiation from it may be much weaker. Mesothorium can be obtained as a 'pure element' only by awaiting its gradual regeneration in thorium salts. It can be isolated simply by precipitation of the thorium with ammonia free from carbonates, eventually after the addition of a little barium, from which the mesothorium can be separated again later by fractional crystallization. But it is self-evident that, even after the lapse of years, only a very small yield by weight can be obtained in this manner. In all practical applications, the radiation value of a mesothorium preparation is increased if it contains any of the longer-lived element radium.

The mesothorium content of radium is generally very small. If the radium has been derived from American carnotite, about $1{\cdot}5 \times 10^{-3}$ of the γ-radiation is due to mesothorium plus radiothorium, whereas if it was obtained from Joachimstal pitchblende this fraction only amounts to 6×10^{-6}.

The extraction of mesothorium on a large scale is carried out in conjunction with that of thorium. In the working up of monazite sand a residue insoluble in sulphuric acid is obtained, and these insoluble sulphates are then worked up in exactly the same manner as that which has been described for the extraction of radium. If there is any doubt as to whether the initial material contains sufficient barium, it is advisable to add a little of a barium salt.

Protoactinium. In the extraction of radium by the Joachimstal process it was mentioned that the 'residual residues' were those parts of the initial material most difficult to bring into solution, and that in addition to acids of the rare earths they also contain tantalum and its higher homologue protoactinium. We obtain a fraction of similar composition by working up pitchblende with sodium bisulphate. By treatment with hydrofluoric acid the acids of the rare earths can be brought into solution, whereas barium and lead remain undissolved. On subsequently digesting with sulphuric acid we again obtain a deposit of tantalic acid, which can be freed from iron and other impurities by means of aqua regia. Another method consists in dissolving out the tantalum directly from the pitchblende by means of hydrofluoric acid and sulphuric acid. Protoactinium is markedly more basic than tantalum and shows a very close relationship to zirconium and hafnium. In the preparation of pure protoactinium use is made of this relationship, the protoactinium being precipitated with zirconium phosphate. The second step consists in the separation of the phosphoric acid by means of alkalis, and the conversion of the zirconium and protoactinium into oxychloride. The separation of zirconium is carried out by means of oxalic acid, after addition of thorium. Finally, the protoactinium is separated from the thorium by the use of hydrofluoric acid. Since the amount of uranium mineral required for the preparation of 1 gm. of radium contains over 0·5 gm. of protoactinium, it has been possible to prepare the latter in a pure state in quantities of this order of magnitude [3].

Actinium. This radio-element is a higher homologue of lanthanum and can be extracted together with this element from all uranium minerals, by means of the methods of separating rare earths dealt with in treatises on chemistry. The concentration of the actinium as compared with the lanthanum salts is, however, met by difficulties similar to those which generally arise in the separation of the rare earths from one another; but the difficulties are intensified on account of the fact that the radiological control of concentration is very tedious, owing to the necessity for awaiting the development of disintegration products from the rayless† actinium. Hitherto it has been established that actinium is more strongly basic than lanthanum, and it is therefore only incompletely precipitated by ammonia, particularly in the presence of ammonium salts. A more convenient method of obtaining it will be rendered accessible when a sufficient amount of its parent protoactinium has been prepared in the pure state; owing to the difference of their chemical properties it will be a simple matter to separate the actinium from the protoactinium.

Ionium. Up to the present we know of no uranium mineral that is absolutely free from ordinary thorium, and for this reason it has not yet been possible to prepare the isotopic element ionium in the pure state. But the mixed element obtained from uranium minerals practically free from thorium consists of equal parts of ionium and thorium, and it accordingly exhibits an appreciably smaller combining weight (see p. 151). Conversely, every thorium mineral contains appreciable quantities of uranium from which slight traces of ionium are formed, and hence, although the atomic weight of the thorium obtained is not altered thereby, its activity is always more or less increased by the presence of this admixed ionium. It is clear that, for the separation of thorium-ionium salts from minerals, the methods that have b developed for ordinary thorium are applicable.

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† The β-radiation from actinium, the existence of which it is necessary to assume in order to explain its transformation into radioactinium (cf. p. 229), is too weak to be detected.

Regarding *radiothorium* it has already been mentioned that it always obtained together with thorium from minerals. It can prepared as a pure element if we start off with mesothorium in a sta of radioactive purity; radiothorium is gradually generated in the me thorium, and after the lapse of sufficient time a simple barium-thori separation can be carried out by means of NH_3. Since the regenera radiothorium is only present in unweighably small quantities, it necessary, in order to obtain visible precipitation, to add, say, a fer salt which is precipitated with ammonia. In this connexion referen should be made to the chemical treatment of the radio-elements of sh life (p. 215).

Radium D. Although RaD is itself almost rayless, it is the constitue of radio-lead which is responsible for the activity of several decad duration, inasmuch as it is the parent of radium E and polonium. can never be obtained in the pure state from minerals, for even thou there may be no ordinary lead in the uranium mineral concerned, t latter inevitably contains radium G, which is likewise an isotope of lea Moreover, as compared with the amount of RaG present, the amou of RaD in the quantitative sense is negligible. On the other hand, Ra can be obtained as a pure element from radon, although the amou obtainable in this way is very small. But since this method belongs those which can only be carried out in general with short-lived radi elements, we shall defer the discussion of it till later. It is worth me tioning, however, that RaD associated with ordinary lead is also a ve valuable material for radiologists, for it serves as a useful source fr which RaE and polonium may be periodically obtained.

Polonium. This element can either be separated together with b muth directly from uranium minerals, or it can be obtained m conveniently from radio-lead. As already mentioned, polonium is bei generated continuously in this mixture of ordinary lead with its isoto RaD and RaG, until it is in equilibrium with the RaD present. Mo over, it is possible to obtain it in fairly concentrated form by recryst lizing the radio-lead, preferably in the form of nitrate. The poloni remains in the mother liquor, and may finally be obtained electrol tically and free from lead and RaE by maintaining a cathode pote tial that is not allowed to fall below $E_c = -0{\cdot}08$ volt.† Gold molybdenum is to be recommended in preference to platinum as t material of the electrodes, because the polonium cannot be redissolved quantitatively from the last-named metal, owing to the formation of an alloy. (Further details on the electrochemical separation of polonium are given in Section B, in connexion with the preparation of RaA, RaE, ThB, and ThC.)

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† Since it is rather troublesome to measure the individual potential of the electr we may make use of the following approximate instructions, which are quite sat in practice. If the current be not allowed to exceed 3×10^{-5} amp. per sq. cm. of cathode surface, the nitric acid solution being $\frac{1}{10}$ N in strength, the polonium is extra in a very pure state.

B. Preparation of the Radio-elements of Short Life

The shorter the life of the radio-element, the more necessary it is for the methods of preparing and purifying it to differ from the ordinary chemical ones, and the more necessary it also becomes to have recourse to measurements of activity as a means of controlling these methods. In addition, the radio-elements of short life occur for the most part towards the end of the disintegration series, later on than the emanations. This circumstance also makes it advisable to describe them separately, for we shall see that the ease with which the emanations can be obtained in the pure state can also be utilized in the isolation of their succeeding products. For this reason we shall consider first the methods of preparing the three emanations.

Being inert gases, the *emanations* are only occluded and never chemically attached to the salts in which they are formed. They usually escape partially even at room temperature, whilst the major portion is liberated by heating, and if the salt concerned be fused, the whole of the emanation can be set free. By carrying out the fusion in a suitably designed apparatus the whole of the emanation can be collected. The hydroxides and halides 'emanate' best, even at room temperatures, whereas sulphates retain large quantities of the emanation. In order to collect radon (radium emanation) quantitatively, it is most convenient to dissolve radium chloride or bromide in water, to allow the sealed-off solution to stand until a sufficient quantity of emanation has been generated, and then to pump off the whole of the gases and transfer them to another vessel. By suitably constructing this vessel we may use it to perform the separation of the rare gases from the admixed gases nitrogen, oxygen, hydrogen, and ozone, by the methods used in gas analysis. The oxygen, hydrogen, and ozone are always formed in consequence of the action of the rays from radium on the water (see Chap. XXIV). It often suffices to explode the explosive mixture of hydrogen and oxygen, which constitutes the major portion of the mixed gases, by sparking in a eudiometer tube similar to those used in gas analysis. If it is required to obtain the radon in still purer form, it is advisable next to free the residual gases from carbon dioxide and water vapour by contact with solid potassium hydroxide, and then to condense the radon by means of liquid air. The uncondensed impurities (nitrogen, hydrogen, rare gases) are then pumped off. an after removal of the liquid air the regasified radon is allowed to strea into the vessel in which it is to be used.

It is obvious that such a complicated purification can only be carri out with the relatively long-lived emanation radon; in the case thoron and actinon we have to content ourselves by liberating an collecting them from the salts or solutions, even though they a contaminated by large quantities of inactive gases. They can never utilized in the form of such intense sources of radiation as radon. b for most purposes, especially the extraction of their disintegrati products, we are not disturbed by the presence of the admixed inacti gases.

The first disintegration products of the emanations are the 'shor lived active deposits', this being the group-name for the produ radium A, radium B, radium C, radium C′, radium C″, and the corr sponding disintegration products of the thorium and actinium di integration series. They are usually obtained by hanging a negativel charged platinum foil in the vessel containing the emanations. Th yield is greater the larger the surface of the platinum foil, and i negative charge only serves as a means of concentrating the acti deposit upon it. The above-named products are deposited on the fo and can be obtained in solution by means of dilute acids, and in lar measure even with hot water. If necessary they can then be separate In order to obtain thorium B and thorium C it is very convenient use an apparatus like that depicted in Fig. 42 (p. 133); situated at t bottom of this apparatus is a glass or platinum dish containing the s of radiothorium or thorium X.

By a shorter or longer exposure of the platinum foil in the emanati we have a means of altering in a known manner the relative proporti of the A-, B-, and C-products, so as to get a favourable yield of t substance desired. In this way it is not difficult by means of ve short exposures to obtain practically pure *radium A* (cf. p. 135). A rule, however, it is necessary to effect a subsequent separation of t individual members of the active deposit. In the thorium and actini disintegration series the A-products hardly call for consideration, owi to their very short life, and even radium A decays so rapidly that removal presents no difficulty, if we require only radium B plus radi C. It suffices to wait about 20 minutes after completion of the exposu before using the active deposit. We have just described the meth of obtaining pure radium A, so that we need now only discuss t methods for the preparation of the *B*- and *C-products* in the pure for

We can achieve a partial separation simply by heating the platinu foil; thus at 800° C. 75 per cent. of thorium B volatilizes and c

20 per cent. of thorium C. But the chemical and electrochemical methods of separation are more effective.

In order to apply them we first proceed to dissolve the active deposit from the platinum foil by means of dilute acids, and then make use of the known methods of separating bismuth and lead. Thus, by means of electrolysis, if the cathode potential reaches the approximate value of $E_c = -0{\cdot}5$ volt, but does not fall below this limit—in a weakly acid solution this corresponds to a current density of 0·4 ma. per sq. cm.—we can separate pure C, whereas the B remains almost quantitatively in solution. The separation of B can be almost completely prevented if we add to the solution a small quantity of isotopic lead in the form of a soluble lead salt, and so ensure that the very small quantity of lead that is separated out below the above-mentioned cathode potential, which is characteristic of lead in this state of dilution, consists almost wholly of inactive lead atoms. If the whole of the bismuth isotopes have been removed, the deposition of which already begins at a potential of $E_c = -0{\cdot}08$ volt, corresponding to about 0·16 ma. per sq. cm., it suffices to increase the terminal voltage so that the cathode potential is below $-0{\cdot}5$ volt in order to be able to separate out the B-products on an arbitrary electrode. If these are required, we should of course avoid previously adding appreciable quantities of inactive lead.

Instead of carrying out an electrolytic separation, a still simpler method of separating out the C-products is to dip a clean sheet of nickel into a hydrochloric acid solution of B and C. As a result of a process which is essentially identical with that of electrolysis, the C-product is deposited on the nickel sheet free from the B-product (cf. p. 162). If platinum be modified electrochemically by charging it with hydrogen, polonium, RaE, ThB, and ThC are deposited on it, without the passage of a current [4].

It is never possible by means of acids to effect the quantitative solution from metal sheets of the radio-elements or of their oxides, which are always present when the sheets are exposed to air. This is due to the occurrence of diffusion of the radio-elements from the surface to the inside of the metal. When this diffusion takes place very slowly, as with polonium on gold, it is possible to effect fairly complete solution of the radio-element from the sheet by means of acid (see p. 215).

It should be emphasized that *radium E*, since it is isotopic with bismuth, can be obtained electrochemically by the same methods as apply to the C-products, and that *radium A* and its isotope *polonium* are still more readily deposited, even at a cathode potential of $E_c = -0{\cdot}35$ volt. In this case we can increase the degree of purity of the radium A or polonium by adding a salt of bismuth, when the deposition of radium C or radium E along with the radium A or polonium is rendered impossible. If it is necessary to separate radium E and polonium fr radio-lead, it is advisable to add antimony, and to precipitate wi pyrogallol in weakly acid solution; the radium E and polonium ar carried down with the antimony, and can then be separated from i electrolytically in the presence of tartaric acid.

In the electrochemical separation of polonium and radium E, radi lead from minerals is not the only source from which they may b derived. We may also use the 'active deposit of long life', which i formed when we allow radon to decay in a closed vessel. *Radium D* i then found on the walls of the vessel, and can be removed by solutio in acids. Radium E and radium F (polonium) are generated contin ously in this solution, and owing to their greater concentration they ca be obtained more conveniently from it by one of the above-describ electrochemical processes than from radio-lead, which is soluble onl in larger quantities of liquid. The best method of proceeding is fir to make the solution ½ N with hydrochloric acid and to move about i it a small clean sheet of silver, which effects practically a quantitati separation of the polonium. The solution is then evaporated to dryne taken up with a 0·2 per cent. solution of hydrochloric acid, and th RaE is deposited on a small clean sheet of nickel. Finally, if we wi to electrolyse out also the radium D, say for the purpose of its purifi tion, it is advisable to separate it anodically as lead peroxide, which readily accomplished in a 7 per cent. solution of nitric acid with a curre density of about 3×10^{-4} amp. per sq. cm., using platinum electrod It may be mentioned that the device of depositing the radio-eleme anodically as peroxide is often suitable also for the purification polonium.

For radio-elements to which they can be applied the electrochemi methods of separation are generally preferable to all others, main because in this way the substances are obtained in a state of chemi as well as of radiochemical purity. Unfortunately they can only contemplated for those radio-elements which are to some extent electr chemically noble, and hence especially for the isotopes of lead, bismut and polonium. In the preparation of very strong polonium sources t electrochemically separated polonium, deposited preferably on rotati electrodes [5], is later concentrated by a process of volatilization a condensation on a smaller surface.

Short-lived thorium isotopes like uranium X_1, radiothorium, a others can be deposited electrochemically on platinum wires from hydrochloric acid solution, with a yield of about 60 per cent.

Another very elegant method of separation is based on the utilizati of the phenomenon of 'radioactive recoil' (see Chap. VI), but its ran of applicability is still more restricted. We may with advantage obt the thallium isotopes *thorium C″* and *actinium C″*, when the particles of these substances recoil in air from a metal plate coated with the active deposit, by collecting them on a negatively charged metal place placed opposite to the activated metal plate. We may also derive pure *radium B* in this way by recoil from radium A, but in this case we must terminate the experiment after the lapse of a few seconds, for otherwise the radium B collected will be mixed with radium C that has been generated from it.

In conclusion, we must deal with those methods of preparing and separating short-lived radio-elements which are most generally applicable, the *chemical methods*. We have accurate information on the chemical nature of all the radio-elements of short life. We know that we are dealing with different kinds of thallium, lead, bismuth, and polonium—these are the products A to G; further, that thorium X and actinium X are isotopes of radium, whereas uranium X_1, uranium Y, and radioactinium are isotopes of thorium, and that mesothorium 2 is identical chemically with actinium, and uranium X_2 with protoactinium. Hence the analytical chemistry of these substances can only afford difficulty inasmuch as they are always present only in exceedingly small concentration. This will be clear if we recall that in ordinary radiochemical work a content of 10^{-11} mol of thorium B per litre would be pronounced a fairly 'strong' solution. An artifice which must always be successful in overcoming the difficulties attendant upon the extreme dilution of these substances consists in the addition of weighable quantities of an isotope. Thus, if we wish to remove thorium B quantitatively from a solution, it suffices to add a little lead nitrate and precipitate the entire lead by means of sulphuretted hydrogen. All the atoms of the mixed element lead so obtained, and consisting of ordinary lead and thorium B, are chemically identical, so that by passing sulphuretted hydrogen through the solution the thorium B must be removed to the same high degree as the lead in the form of practically insoluble lead sulphide.

A disadvantage of this method consists in the fact that once such mixing has taken place the process is practically irreversible, and hence the radio-element can never again be obtained in concentrated form. For this reason we should only revert to this method of adding an isotope when we are concerned with the quantitative removal and not with the preparation of a radio-element. In the latter case it is always advisable not to use an isotope but to have recourse to a related element as a carrier in the precipitation reaction. This is analogous to the addition of barium in the extraction of radium or mesothorium already discussed, for in this way we can effect a separation from the more distant chemical elements, and still finally bring about the separation of the radio-element from the added barium. Similarly, it is often better to precipitate, say, radium E by the admixture of lead rather than of bismuth, for then it can easily be separated again by electrochemical means (see above). Likewise we should make use of zirconium or cerium rather than thorium for the separation of uranium X_1, and so on.

When a related element and not an isotope is used, we can no longer maintain that the radio-element must also be removed by every quantitative precipitation of this substance. Lead sulphate, for instance, would leave radium E in solution, whereas lead sulphide would remove it quantitatively. In such cases the adsorption and precipitation rules which we have already discussed is applicable (see p. 163 et seq.). A radio-element will be adsorbed and precipitated by those deposits the anions of which form with the radio-element concerned a compound which has a low solubility in the solvent used. In the place of the isotope we should thus be able to use any other element for mixing purposes so long as it forms, like the radio-element, an insoluble precipitate with the anion in the solution. Instead of the hydroxide precipitation of the thorium isotopes we may utilize the hydroxide precipitation of iron salts, or in place of the sulphate precipitation of the lead isotopes we may use the sulphate precipitation of barium salts, and so on.

It is not necessary for us to do more than to direct attention to these rules here, since they have done invaluable service in the entire large domain of the analytical chemistry of the radio-elements, in spite of few exceptions that have not yet been fully explained. Our knowledge of these rules enables us to give a clear summary of the methods of separation of the radio-elements of short life which have been tested hitherto, and to predict new and suitable methods. It must be left to the analytical experience of the chemist to decide which individual process is to be recommended, in accordance with the special problem on hand.

REFERENCES

For further information on the topics of this chapter reference should be made to *Le Radium et les Radio-éléments*, by **Maurice Curie** (Baillière, Paris, 1925) where the development of the radium industry up to 1925 is fully treated; to *Radium und Isotope*, by O. **Erbacher** (Gmelin's *Handbuch der Anorgan. Chemie*, 8th edn., Berlin, 1928), and to the books mentioned at the end of Chap. X (p. 153).

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XXIII

THE PROPERTIES OF THE INDIVIDUAL RADIO-ELEMENTS

In this chapter we shall discuss the individual radio-elements in the order of their production from the parent substances uranium, protoactinium, and thorium, and in each case we shall give the most important data which serve to characterize that radio-element from the physical and chemical points of view. It will suffice if we are brief here, because in the preceding and more general chapters we have also frequently made reference to the special properties of the radio-elements. Thus we shall only deal with the methods of preparation in so far as in one case or another the systematic treatment given in Chapter XXII requires to be supplemented from the practical viewpoint. In conclusion, we shall devote some space to the radioactive elements potassium, rubidium, and samarium, which stand in an isolated position as compared with the rest of the radio-elements, and which have not yet been so thoroughly investigated as these.

The significance of the symbols used is as follows: Z = atomic number; A.W. = atomic weight; C.W. = combining weight; T = half-value period†; R = range in cm. in air at 760 mm. pressure and 15° C.; μ = coefficient of absorption in aluminium, measured in cm.$^{-1}$

A. The Uranium Series

1. Uranium

Uranium is a mixture of three isotopes, uranium I (^{238}U), uranium II (^{234}U), and ^{235}U, which is probably identical with actino-uranium, the parent of the actinium series [1] (see also p. 230). The period of uranium II being so much shorter than that of uranium I, the mixed element 'uranium' contains only 0·008 per cent. of uranium II, and less than 1 per cent. of the isotope ^{235}U. The rate of decay of ^{235}U is not exactly known, but it is probably about 6 times that of

	Uranium I	*Uranium II*
Z	92	92
A.W. . . .	238·07	234
T	$4·4 \times 10^9$ years	$3·4 \times 10^5$ years
Radiation . .	α	α
R	2·63 [2]	3·18 [2]
Parent element .	—	UX_2
Daughter element .	UX_1	Io

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† The disintegration constant (λ) can be calculated simply from T by means of the relation $\lambda = \dfrac{\log_e 2}{T} = \dfrac{0·693}{T}$ (see p. 127).

uranium I. We shall not deal with the chemical properties of urani here, as they are to be found in every text-book of chemistry. In rad active investigations we generally use the grey-black oxide of urani U_3O_8 or the yellowish fluorescent uranyl nitrate $UO_2(NO_3)_2 \cdot 6H_2O$, t former as a standard for α-ray measurements, and the latter for t preparation of uranium X. For information as to the occurren uranium minerals see Table 52, p. 273, and on methods of extra radium from them see p. 207 et seq.

The α-activity of uranium in equilibrium with all its disintegrat products is 4·73 times as large as that of uranium alone. The t α-radiation from 1 gm. of uranium in the form of an infinitely t layer, and utilizing both sides of the layer, would maintain in an ioni tion chamber a current of 1·37 e.s.u., or $4 \cdot 56 \times 10^{-10}$ amp. A layer U_3O_8 of area 1 cm.², if only the radiation from one side of it be tak into account, would maintain in an ionization chamber a current $1 \cdot 73 \times 10^{-3}$ e.s.u., or $5 \cdot 76 \times 10^{-13}$ amp.

2. Uranium X_1 and Uranium X_2

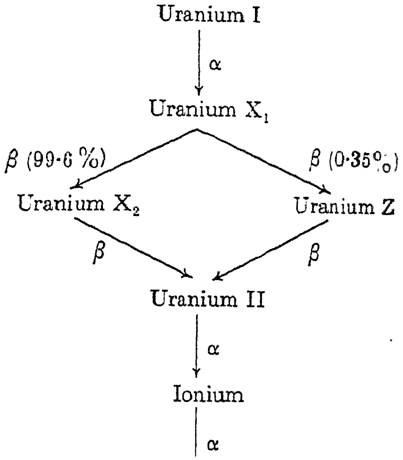
Uranium X_1 is an isotope of thorium (see Table 38, p. 152); it therefore be most conveniently separated from solutions of urani salts by precipitation with iron or zirconium hydroxide (see also p. 2

	Uranium X_1	*Uranium X_2*	
Z	90 (= thorium)	91 (= protoactinium)	
A.W.	234	234	
T	24·5 days	1·14 minutes	
Radiation	β	β, γ	
μ	460	β	γ
		18	0·14
Parent element	U_I	UX_1	
Daughter element	UX_2	U_{II}	

Uranium X_2, an isotope of protoactinium, is obtained from soluti of uranium X_1 by electrolysis or by joint precipitation with tantal oxide.

3. Uranium Y and Uranium Z

The genesis of these two products, both of which are found in urani salts, is not yet perfectly clear. Uranium Y (T = 24·6 hours) is isotope of thorium, and uranium Z (T = 6·7 hours) an isotope protoactinium. Both are β-rayers (μ_{UY} = c. 54 and 600, μ_{UZ} = c. 1 and it follows from the smallness of their contribution to the t activity of uranium salts that they cannot occupy a place in the m disintegration series. Uranium Y is most probably a disintegrat product of the uranium isotope ^{235}U and the parent of protoactinium, and hence of the actinium series (cf. Table 34, p. 143). On the other hand, uranium Z has hitherto been regarded as a daughter element of the dual β-disintegration of uranium X_1, but it is just possible that it may be a decay product of a uranium isotope other than ^{238}U (see p. 142). On the former view the beginning of the uranium-radium disintegration series would be represented schematically in the following way:



4. Ionium and Radium

Ionium, an isotope of thorium, has not yet been prepared in the pure state: a thorium preparation relatively rich in ionium (*re* its origin, see p. 151) was found to contain 30 per cent. of ionium, and yielded a combining weight of 231·51 (A.W. of ionium = 230, C.W. of thorium = 232·12).

	Ionium	*Radium*
Z	90 (= thorium)	88
A.W.	230	226·05
T	$8{\cdot}3 \times 10^4$ years	1,590 years
Radiation . .	α	α (β) (γ)
R	3·2	3·39
Parent element .	U_{II}	Io
Daughter element .	Ra	Rn

We have already described the processes used in the preparation of radium. It is generally brought into the market in the form of the chloride or bromide, mixed with the corresponding salt of barium. One of the international radium standards is kept in Paris and consists of

22·23 mg. of anhydrous $RaCl_2$; the other is kept in the Vienna Ra Institute and contains 30·75 mg. of anhydrous $RaCl_2$. Both standar were prepared in 1934 by Hönigschmid, and are composed of t purest $RaCl_2$, free from every trace of barium. The price of radiu preparations is determined by their content of the element radiu When the extraction of radium was limited to the small producti St. Joachimstal, the price of 1 mg. radium was between £20 and £ Moreover, this price was not greatly altered in consequence of the m extensive production of the element in America. But with the discove of the large mineral sources in the Belgian Congo and in Canada (Gre Bear Lake), a marked diminution of the price has been effected. the present time the price of radium is less than £5 per milligram.

Since radium, in spite of its rarity, has already been produced quantities of several hundreds of grammes (see p. 211), it is no longer difficult matter to determine the properties of this element by t methods usually used in chemistry and in physics. The eviden adduced from its spectrum and from the solubility of its salts, et all showed it to be a higher homologue of barium. Thus the solubili of its sulphate is smaller than that of any of the other sulphates of t alkaline earths, as is shown in Table 46.

TABLE 46

Solubility of the Sulphates of the Alkaline Earths

	Solubility at 25° C. in per cent. by weight (gm. of the sulphate in 100 gm. of the solution)
$CaSO_4$	$2{\cdot}1 \times 10^{-1}$
$SrSO_4$	$1{\cdot}5 \times 10^{-2}$
$BaSO_4$	$2{\cdot}3 \times 10^{-4}$
$RaSO_4$	$2{\cdot}1 \times 10^{-6}$

Table 47 gives the solubilities of the bromides, chlorides, and nitra of barium and radium.

TABLE 47

Solubility of Barium and of Radium Salts
(at 20° C., in per cent. by weight)

	Barium	*Radium*
Bromide	51	41·4
Chloride	26·3	19·7
Nitrate	7·9	12·2

It is very surprising that the solubility of radium nitrate is grea than that of barium nitrate, and that in spite of this the radium becomes concentrated in the barium salt deposited when the mixed nitrates are subjected to fractional crystallization, just as in the case of the mixed bromides or chlorides.

Radium compounds decompose in the course of time under the action of their radiations; thus radium chloride gives off chlorine, and is partially converted into the chlorate and the oxide.

For the most part the salts of radium are available in quantities of only a few milligrams, and mixed with barium, so that it is most convenient to determine them quantitatively by the measurement of their radioactivity. In contrast to the method of weighing, the degree of purity of the radium salt is without significance in estimations by this method. We must compare the unknown preparation with a radium salt of known radium content which has been standardized directly or indirectly by means of the International Standards. When the intensity of the γ-rays is used as the basis of the measurement, the method has a further advantage in that the preparation can remain in a sealed-off glass tube, which is the usual mode of packing.[†] Very weak preparations must be brought into solution, and the most accurate method of estimating them is by the measurement of their radon content. In this method, when the radon is in equilibrium with the amount of radium present, it is driven into an electroscope that has been previously calibrated by known quantities of radon.

With the aid of this extremely sensitive method quantities of radium as small as 10^{-13} gm. can be measured accurately to within a few per cent., and hence it has been possible to establish the presence of traces of radium in all minerals. For further information see Chapter XXV (p. 274).

A weak β-radiation from radium is also mentioned in the table (p. 223). This does not originate in the nucleus, otherwise an isotope of actinium would be detectable as a disintegration product. It is of secondary origin, being released from the K- and L-levels by γ-rays (cf. p. 102). The value of the absorption coefficient is $\mu = 312$ cm.$^{-1}$ The γ-radiation proper to radium only amounts to approximately 1 per cent. of the total γ-radiation emitted by a radium preparation which is in equilibrium with its disintegration products. The α-activity of radium, exclusive of that of its disintegration products, is 0·56 times the α-activity of uranium, which of course always contains the two α-rayers U_I and U_{II} (in this connexion cf. p. 29).

[†] It has been suggested that the unit of measurement for such γ-ray measurements should be called an 'eve'. This is the ionization produced per sec. in 1 c.c. of air at N.T.P. by the γ-rays from 1 gram of radium at a distance of 1 cm. (Cf. the unit of dosage on p. 57.)

5. Radon (Radium Emanation)

Radon is the heaviest of the rare gases, and because of its inab to enter into chemical reactions, and from the nature of its spectra it was possible at an early stage to allot it a corresponding place in periodic classification. Later on it was obtained in sufficiently la quantities for the determination also of other of its constant boiling-point has the value −62° C., its freezing-point −71° C., an critical temperature +105° C. At room temperature, radon is di buted in the proportion of 1 : 3 between water and an equal volume

	Radon (Rn)
Z	86
A.W.	222
T	3·825 days
Radiation . .	α
R	4·12
Parent element .	Ra
Daughter element .	RaA

air in a closed vessel, so that its distribution coefficient α has the v 0·3. With increase in temperature the solubility decreases in accordance with Henry's law, as shown in Table 48. The solub

TABLE 48

Distribution of Radon between Water and Air

Temperature in °C.	*Distribution coefficient (α) between water and air*
0	0·510
10	0·350
20	0·255
30	0·200
40	0·160
50	0·140
60	0·127
70	0·118
80	0·112
90	0·109
100	0·107

is also reduced by the addition of salts to the water; thus for uni- salt solutions at 18° C. the value of α is about 0·16. The distrib coefficient between blood and air amounts to 0·42 at body tempera The human skin is somewhat permeable to radon, but the radon enters the system during radium baths does so primarily by way lungs [3].

Organic liquids dissolve very much more radon than water; th ne $\alpha = 6{\cdot}3$, petroleum $\alpha = 10$, hexane $\alpha = 17$, olive oil $\alpha = 28$, nd so on. The coefficient of diffusion of radon in water at 14° C. mounts to 0·82 $\text{cm.}^2\ \text{day}^{-1}$. Also solid bodies like rubber, paraffin wax, latinum black, and especially charcoal adsorb radon very strongly. Under certain circumstances radium preparations occlude an appreciable fraction of the radon produced in them. Such salts which emanate ally can be improved by moistening, pulverizing, or by converting hem into the hydroxide or halide. Solid radium salts emanate much ore strongly when they are deposited on carrier substances with a arge surface area. In this way it has been possible, by binding radium arbonate to iron hydroxide, to prepare sources of radon, the emanating ower of which remained for years at over 90 per cent., a fact which very welcome for various practical applications.

The volume of radon in equilibrium with 1 gm. of radium is 0·65 mm.^3 $= 6{\cdot}5 \times 10^{-6}$ gm.). This quantity of radon is called 1 'curie'; both it nd the thousandth part of it ('milli-curie') are used as units of measurement for quantities of radon. For concentrations of radon the unit of measurement adopted is called 1 'mache'; thus spring-water has a radon concentration of 1 mache when the quantity of radon in 1 litre f this water would produce a saturation current of 1×10^{-3} electrostatic units, if it were transferred to an electroscope and if its radiation n all directions were utilized. One mache unit is equal to $3{\cdot}6 \times 10^{-10}$ uries per litre.† The radon content of strongly radioactive springs ften amounts to several thousand mache units. Examples of this are ontained in Table 49. Values for the radium content of sea- and river-aters are given on p. 275.

TABLE 49

Radon Content of Several Springs, expressed in Mache Units

lema	c. 3,000	Ischia (Old Roman Spring) .	370
mstal (Water in Mine) .	2,050	Gastein (Reissacher Stulm) .	300
ach (Wettin Spring) .	2,000	Aix-les-Bains (Alum Spring) .	56
mstal (Spring Head) .	600	Carlsbad (Mühlbrunnen) .	32

9. The Short-lived Active Deposit of Radium (RaA, RaB, RaC, RaC′, RaC″)

The first five disintegration products of the gas radon are isotopes of the metals polonium, lead, bismuth, or thallium, and since they are solids, they have the tendency to be deposited as soon as they are produced. Moreover, with the exception of a very small fraction they

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* In 1921 a new unit was suggested for the measurement of concentrations of radon: 1 'eman' = 1×10^{-10} curies per litre.

	RaA	RaB	RaC	RaC′
Z	84 (= polonium)	82 (= lead)	83 (= bismuth)	84 (= polonium)
A.W. . . .	218	214	214	214
T	3·05 min.	26·8 min.	19·7 min.	10^{-6} sec.
Radiation . .	α	β, γ	α, β, γ	α
R	4·72		α 4·1	6·96
μ		β: 890, 77, 13 γ: 230, 40, 0·57	β: 50, 13 γ: 0·23, 0·127	
Parent element .	Rn	RaA	RaB	RaC
Daughter element	RaB	RaC	99·96% RaC′ 0·04% RaC″	RaD

allowed to decay (cf. pp. 137 and 218); its electrochemical properties correspond exactly to those of ordinary lead.

Radium E is an isotope of bismuth. In view of its short period of life it would appear to be impossible to obtain it in visible quantities. Absorption coefficients of 7·4 and 0·85 cm.$^{-1}$ have been found for the radiation from radium E in copper. RaE has been produced artificially by bombarding bismuth with 5×10^6 e.V. deuterons [4].

	RaD	RaE	RaF
Z . .	82 (= lead)	83 (= bismuth)	84 (= polonium
A.W. .	210	210	210
T . .	22 years	5·0 days	140 days
Radiation .	β, γ	β, γ	α
			3·87
	γ 5,500 1·17	γ 43 0·24	
Parent element .	RaC′	RaD	RaE
Daughter element	RaE	RaF	RaG

Radium F, or polonium, is the most important representative of the element of atomic number 84; the other types of this element, the 'A'- and 'C′'-products, are still less stable. The γ-rays emitted by RaF are of very feeble intensity; 7 γ-quanta are emitted for every 10^6 α-particles. The average energy of these quanta amounts to 850×10^3 e.V. The chemical properties of this otherwise unknown element have to be studied with RaF, and in part are already very well known. It resembles very strongly its atomic analogues bismuth and tellurium, as is shown by the whole of its behaviour in analytical chemistry, by its electrochemical potential, which lies near to that of silver, and by its ability to form a gaseous compound with hydrogen. Like tellurium hydride, polonium hydride decomposes in the moist state in a few minutes. As already mentioned on p. 165, polonium occurs in the colloidal state in neutral or in weakly acid solutions.

B. THE ACTINIUM SERIES

1. Protoactinium and Actinium

	Protoactinium	*Actinium*
Z	91	89
T	$3 \cdot 2 \times 10^4$ years	c. 13 years
Radiation . .	α	β
R	3·67	
μ		unknown
Parent element .	UY (?)	Pa
Daughter element .	Ac	RdAc

It will be seen from the above table that uranium Y is presumed to be the parent of protoactinium; this is due to the fact that this arrangement fits in well with the displacement laws and with the quantitati relations known for the actinium series (see Chap. XIII), but it has n yet been possible to obtain direct proof of the genetic connexion between UY and Pa. The actinium series is present in a constant proportion in all uranium minerals, and is responsible for 4 per cent. of the total activity. In early geological times the proportion must have been much larger, in consequence of the relatively more rapid decay of actino-uranium (^{235}U), the parent of the actinium series. This parent element would then be a more prominent constituent in the mixed element uranium than it is to-day, when its relative abundance is estimated to be less than 1 per cent. and its rate of disintegration about 6 times that of uranium I.

The chemical properties of protoactinium are such as would be expected of a higher homologue of tantalum (see p. 212). The separation of protoactinium from tantalum is based on the fact that the basicity of Pa_2O_5 is stronger than that of Ta_2O_5, and is not much different from that of hafnium and zirconium. By making use of this analytico-chemical difference it has not only been possible to separate protoactinium from the accompanying tantalum, by precipitating the protoactinium along with zirconium phosphate, but also to prepare a few decigrams in the chemically pure state.

Actinium is a higher homologue of lanthanum, and since it is a new element it would be interesting if it could be prepared in the pure state. Hitherto this has not been possible, and owing to the short life of the element it is doubtful whether weighable quantities will b obtainable.

2. Radioactinium, Actinium X, and Actinium Emanatio (Actinon)

	RdAc	AcX	AcEm (Ac
Z . . .	90 (= thorium)	88 (= radium)	86 (= emanatio
T . . .	18·9 days	11·2 days	3·92 sec.
Radiation .	α, β, γ	α	α
R . . .	4·68 (α)	4·37	5·79
μ . . .	γ 175 25 0·19		
Parent element	Ac	RdAc	AcX
Daughter element	AcX	An	AcA

Special attention is merited by one rather striking feature contain in the above table. AcX emits α-rays of smaller average velocity th RdAc, which has a longer period of life. This constitutes a breach of t general rule relating to the connexion between period of life and ran (p. 146). As with the β-rays from Ra and RdTh, those emitted RdAc may be assumed to be of secondary origin.

For the chemical separation of RdAc from Ac and simultaneously from X, we utilize the fact that thorium is readily precipitated in weakly d solution by means of thiosulphate or hydrogen peroxide. In order obtain a visible deposit we may add a trace of a thorium salt, or, still etter, of a salt of the non-isotopic element zirconium (cf. p. 219 et seq.) efore the precipitation. In this way we obtain AcX together with Ac the filtrate, and it may be freed from Ac by repeated precipitation ith ammonia, remembering of course that we must add a little iron r similar element before each precipitation with ammonia, in order to tain a deposit the anions (OH′-groups) of which then act as carriers r the Ac (cf. the rule on p. 220). We may obtain AcX in a very pure rm by means of recoil from solid preparations of RdAc (cf. p. 218).

Like radon, actinon is an inert rare gas, the physical constants of hich (coefficient of diffusion, solubility, etc.) have not been determined ith any great accuracy, owing to its extremely short period of life nd the correspondingly small quantities of it available. In view of the otopy of the two emanations, however, we may assume with confidence hat the properties of An are identical with those of Rn.

3. The Active Deposit of Actinium (AcA, AcB, AcC, AcC′, AcC″)

	AcA	AcB	AcC	AcC′	AcC″
. . .	84 (= polonium)	82 (= lead)	83 (= bismuth)	84 (= polonium)	81 (= tha lium
. . .	2×10^{-3} sec.	36·0 min.	2·16 min.	5×10^{-3} sec.	4·76 mi
diation . .	α	β, γ	α, β	α	β, γ
. . .	6·58		5·5 (α)	6·6	
. . .		β: large γ: 120 31 0·45			β 44·5
ent element .	An	AcA	AcB	AcC	AcC
ghter element	AcB	AcC	0·16% AcC′ 99·84% AcC″	AcD (?)	AcD

A comparison with the table on p. 228 reveals immediately the great imilarity, as regards their sequence and radiation, between the individual members of the active deposit of actinium and the corresponding members of the short-lived active deposit of radium. Apart from the different numerical values of T, R, and μ, the following important differences exist. In the first place, with AcC the majority of the atoms disintegrate with emission of α-radiation into AcC″, whereas in the case of RaC practically all the atoms are transformed into RaC′ with emission of β-rays; in the second, AcD is already the stable end-product of the actinium series, whereas RaD, although it is much more stable than the previous members of the series, still possesses the character of

a radio-element, and is the first member of the 'long-lived acti
deposit' of radium, which has no analogue in the actinium series.

C. THE THORIUM SERIES

1. Thorium, Mesothorium 1, and Mesothorium 2

	Th	$MsTh_1$	MsTh
Z	90	88 (= radium)	89 (= acti
A.W. (and C.W.)	232·12	228	228
T	$1{\cdot}34 \times 10^{10}$ years [5]	6·7 years	6·13 h
Radiation	α	(β)	β, γ
R	2·59 [6]		
μ			β 40–20
Parent element		Th	MsTh
Daughter element	$MsTh_1$	$MsTh_2$	RdTh

The element thorium is the parent of a radioactive series which
completely independent of the uranium-radium and the actinium di
integration series. This is evidenced by the fact that the contributi
of the two series towards the activity of various minerals fluctua
between very wide limits. Thus we are familiar with uranium miner
that are practically free from thorium and its decay products, an
conversely, there are thorium minerals which contain very little ur
nium, and hence also very small quantities of ionium and radium. Th
chief source of thorium is monazite sand, which contains up to 18 p
cent. ThO_2. A few rare minerals are much richer in thorium, such
the thorianite found in Ceylon, which may contain over 50 per cen
ThO_2. A résumé of the composition and properties of the most impo
tant thorium minerals is given in Table 52 on p. 273. The separati
of thorium from the other rare earths is not a simple matter.
information on the preparation of pure thorium is contained in chemi
text-books. In radioactive investigations thorium is generally used
the form of nitrate or hydroxide. The nitrate is used when we requi
a soluble salt for the purpose of separating out ThX, and the hydroxi
for the collection of thoron, owing to the fact that it 'emanates' free

We have already spoken (Chap. XXII, p. 212) about the preparati
of *mesothorium*, and of the impossibility of obtaining it completely fr
from radium. We can determine the approximate radium content
mesothorium preparations on the market without opening them.
carrying out absorption measurements of the γ-rays for various thi
nesses of the absorbing metal sheets (see p. 55). More reliable val
are obtained by determining the amount of radon produced in them

We are unable to detect the rays emitted by mesothorium 1, but fr the fact that the succeeding product mesothorium 2 has an atomic number 89, we must conclude that each atom of the former loses a particle when it is transformed into an atom of the latter. The activity is due exclusively to the radiation from the disintegration products, especially that of mesothorium 2, which, owing to its short half-value period, is present practically in its equilibrium amount even after a period of 3 days. An appreciable quantity of radiothorium will be present in older preparations of mesothorium, since the half-value period of RdTh is only 1·9 years. In consequence of this we have to take account of the likewise very penetrating γ-radiation from ThC″. Fig. 48 indicates the manner in which the resulting total activity of a mesothorium preparation' alters in the course of years.†

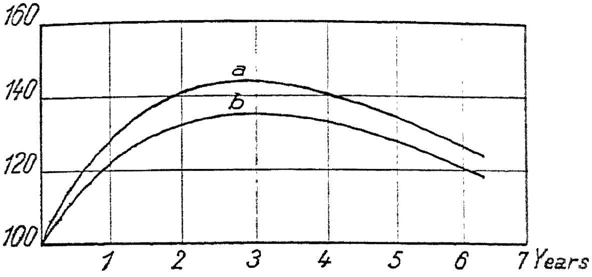

Fig. 48. Variation of the γ-Activity of Mesothorium Preparations with Time.

Curve *a* was obtained with freshly prepared mesothorium free from radium, whilst curve *b* was obtained with a new preparation of mesothorium containing radium (cf. footnote on p. 55). In these measurements the rays were passed through lead filters of thickness 3·3 mm. In both cases the maximum intensity of the radiation was attained after a period of about 3 years, but the increase was greater for the preparation free from radium than for that containing radium. In the former case the activity rose from 100 to 143·8, or by about 44 per cent., whereas in the latter case it rose from 100 to 135, or by 35 per cent. If the measurements had been carried out with lead filters 5 mm. instead of 3·3 mm. thick, the form of the curves would have been essentially the same, but the rise would have been slightly more pronounced for the mesothorium containing radium, owing to the fact that the γ-radiation from radium relative to that from mesothorium is somewhat less effective after passing through 5 mm. of lead than after passing through 3 mm.

The amount of MsTh available by weight is always extremely small.

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† Since the hardnesses of the γ-radiations from $MsTh_2$ and ThC″ are different, the measured proportions of the two radiations also depend somewhat on the choice of the apparatus used for the measurements (thickness of the absorbing layers).

for $2{\cdot}7 \times 10^9$ gm. thorium are required to produce an equilibrium amo of 1 gm. $MsTh_1$. On the other hand, the γ-activity of 1 gm. radiu equivalent to that of about $\frac{1}{500}$ gm. mesothorium, and hence to t quantity in equilibrium with about 5×10^6 gm. thorium.

2. Radiothorium, Thorium X, and Thorium Emanation (Thoro

	Radiothorium	*Thorium X*	*Th*
Z . . .	90 (= thorium)	88 (= radium)	86 (= rad
A.W. . .	228	224	220
T . . .	1·90 years	3·64 days	54·5 sec
Radiation . .	α, β	α	α
R . . .	4·02 (α)	4·35	5·06
μ . . .	β 420		
Parent element .	$MsTh_2$	RdTh	ThX
Daughter element	ThX	Tn	ThA

The β-rays from RdTh do not originate in the nucleus, but are secondary origin (cf. p. 102), like those from Ra and RdAc. They probably released from the L- and M-levels by a γ-radiation which not yet been detected directly.

We have already mentioned the method of preparing radiothori in Chapter XXII. ThX may be obtained periodically from a prepa tion of RdTh by precipitating this together with iron, aluminium, similar elements by means of ammonia, when the ThX remains in filtrate (cf. the method described above for the preparation of isotope AcX). Radiothorium and thorium X are chiefly used as sou of thoron and of its short-lived disintegration products. It is advis to maintain preparations that have been made for this purpose manently in a moist condition, because then they allow the emana to escape much more readily.

3. The Active Deposit of Thorium (ThA, ThB, ThC, ThC′. Th

	ThA	ThB	ThC	ThC′	Th
Z . . .	84 (= polonium)	82 (= lead)	83 (= bismuth)	84 (= polonium)	(= t li
A.W. . .	216	212	212	212	2
T . . .	0·14 sec.	10·6 hours	60·5 min.	c. 10^{-11} sec.	3·1 m
Radiation . .	α	β, γ	α, β	α	β
R . . .	5·68		4·78 (α)	8·62	
μ . . .		β 153 γ 160 32 0·36	β 14·4		β 21·6
Parent element .	Tn	ThA	ThB	ThC	Th
Daughter element	ThB	ThC	65% ThC′ 35% ThC″	ThD	Th

Comparisons of the accompanying table with that deposit of actinium and with that for the short-lived active deposit of radium (pp. 231 and 228) reveal the great similarity between these parts of the three disintegration series. Characteristic of the thorium series is the branching ratio of the C-product. In this case comparable amounts disintegrate with the emission of α- and of β-rays, whereas with AcC almost the whole follows the α-branch, and with RaC the main disintegration is attended by the emission of β-rays. According to the displacement laws it is to be expected that the two branch series will lead to the same end-product, the lead-isotope ThD, and as a matter of fact a type of lead with the atomic weight calculated for ThD has been found in thorium minerals (cf. p. 151). It has not yet been established whether both types of lead, produced in the proportion by weight of 35: 65, are stable, or whether one of them is transformed into an isotope of bismuth with emission of β-rays (cf. p. 144).

Although the A-product is of longer life than in the case of the actinium series, it has likewise not yet been possible to separate it from the emanation. Both products reveal themselves in the fact that the scintillations produced by the emanations are always observed to occur in pairs. In the case of actinium ($T_{\mathrm{AcA}} = 2 \times 10^{-3}$ sec.) the two members of such a pair of scintillations appear simultaneously, whereas in the case of thorium ($T_{\mathrm{ThA}} = 0{\cdot}14$ sec.) a distinct interval between the two scintillations is recognized, albeit a short one.

ThB and ThC are particularly suitable for use as indicators in physical and in chemical investigations, and have often been used for this purpose (cf. Chap. XVIII). This is due to the fact that they are relatively stable and their half-value periods are so different that they can conveniently be determined quantitatively, one along with the other.

The active deposit of thorium also emits α-particles of ranges 9·8 and 11·6 cm. For every 10^6 α-particles of range 8·62 cm. (ThC′) there are respectively 65 and 180 of these particles of long range (cf. p. 27).

D. POTASSIUM, RUBIDIUM, AND SAMARIUM

	Potassium		Rubidium	Samarium
Z	19		37	62
W. . . .	39·096		85·48	150·43
A.W. . . .	39; *40*†; 41		85; *87*†	144; 147; 148; 149; 150; 152; 154
T	$1{\cdot}9 \times 10^9$ years		5×10^{10} years	$1{\cdot}02 \times 10^{12}$ years
Radiation . . .	β	γ	β	α
. . . .	75; 29	0·59 in lead	700; 140	
R				1·15 cm.

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[*] Radioactive isotope. The half-value periods given for potassium and rubidium are

From amongst the chemical elements that have been known fo long time it has been found by very careful measurements that th are three, apart from uranium and thorium, which emit a constant very weak radiation. These are the elements potassium, rubidium, a samarium. There is some evidence also that neodymium emits β-ra

Potassium and rubidium are β-rayers, and although the rays emi by potassium are the more penetrating, the number of β-parti ejected from equal quantities by weight is markedly greater in the of rubidium. Measurements with a tube counter have yielded for t ratios of the numbers of β-particles emitted in the same time by eq amounts of potassium, rubidium, and uranium the values 1:16: In this estimate account is taken of only one of the β-raying com nents resulting from uranium, viz. UX_1. The limit of hardness of softer component of the β-radiation amounts to 400×10^3 e.V. potassium and to 100×10^3 e.V. for rubidium, whereas the limit hardness of the fast β-rays from potassium is situated at 700×10^3 e and from rubidium at 250×10^3 e.V. The γ-radiation from potassi is almost as hard as the hardest γ-radiation emitted by radium (Ra but its intensity is extremely small. The ratio between the intensi of the γ-radiations from 1 gm. potassium and from RaC (in e librium with 1 gm. radium) has the value $1:3\times10^{10}$. In the disinte tion of 100 atoms of potassium only three γ-quanta are emitted. e with an energy of 2×10^6 e.V.

By means of experiments devised for the purpose it has been sh that the radioactivity of potassium and rubidium compounds is stri proportional to their respective potassium and rubidium contents. that the radiation has the same intensity at the temperature of li air as at room temperature. There can be no doubt, therefore, tha are here dealing with the phenomenon of radioactive disintegration is a striking fact that, apart from samarium (see later), the elem potassium and rubidium stand in an isolated position, for all the o natural radio-elements belong to disintegration series consisting many members. The discovery of artificial radioactivity, howe has thrown important light on this remarkable phenomenon pp. 115 and 238).

In order to decide which of the isotopes of potassium is respon for the emission of β-rays, a partial separation of the potassium isot was undertaken, and both the combining weight and the activity of 'heavier' fraction obtained were compared with those of ordi potassium. The determination of the combining weight of the h

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those of ^{40}K and ^{87}Rb; in the case of samarium the radioactive isotope is not kn and hence the period given in the table is that which samarium would have whole of the mixed element were radioactive.

fraction revealed an increase in the concentration of ^{41}K of about 7 per cent., whereas the β-activity of the heavy fraction was found to have increased by only about 4 per cent. as compared with ordinary potassium. Now for the same conditions of experiment the gain in the concentration of a potassium isotope can depend only on the difference in the mass of that isotope from that of the isotope ^{39}K. From the fact that it is more difficult to increase the concentration of the radioactive isotope than it is to increase that of ^{41}K, it follows that the mass of the radioactive isotope must differ by less than 2 units from that of ^{39}K, so that it must have the value 40. This conclusion is supported by the fact that it has not been possible, either by the mass-spectrograph or on the basis of atomic-weight determinations, to detect the presence of a calcium isotope of mass 41 in potassium minerals of great geological age. It is interesting to note that the presence of ^{40}K in ordinary potassium has been established to the extent of about 1:8,000 by means of a mass spectrograph of high resolving power [7], and that by use of an instrument of high intensity it has also been possible to separate in minute amounts the three isotopes of potassium. Measurements of their activity show not only that ^{40}K is radioactive, but that it is the isotope responsible for the two known groups of β-rays emitted by potassium [8]. From the above-mentioned concentration of ^{40}K in the mixed element potassium, and the apparent half-value period of potassium, $1{\cdot}5\times10^{13}$ years, which follows from the number of β-particles emitted annually by 1 gram of potassium, the half-value period of ^{40}K works out to be *c.* 2×10^{9} years.

By analogy with potassium it seemed not unlikely that the radioactivity of rubidium would be due to an isotope of mass 86, present in quantities too small to be detected by the mass spectrograph, but this view is not substantiated by recent experimental work. Investigations carried out with a lithium mica from Manitoba, Canada, showed that it contained 2–3 per cent. of rubidium and a slight amount of strontium. The strontium was carefully extracted from about 1 kg. of this mineral, and about 250 mg. of strontium carbonate were obtained; calculation indicated that at least the major part of this strontium must have been produced in the mineral by the disintegration of rubidium. A careful mass-spectrographic examination of the strontium preparation has shown that it consists almost wholly (99·7 per cent.) of the strontium isotope ^{87}Sr,[†] and the conclusion seems inevitable that the isotope of rubidium responsible for the radioactivity of this element is ^{87}Rb [9]. From this work it also appears that the value of the apparent half-

[*] Ordinary strontium has the following approximate composition, as determined by the mass-spectrograph: 10 per cent. of ^{86}Sr, 7 per cent. of ^{87}Sr, and 83 per cent. of ^{88}Sr (see p. 153).

value period of rubidium previously accepted ($4 \cdot 3 \times 10^{11}$ years) is to high, and that the true value lies nearer 2×10^{11} years. In view the abundance of ^{87}Rb in ordinary rubidium (27 per cent.), the val of the half-value period of ^{87}Rb must be about 5×10^{10} years.

Until comparatively recently it was quite impossible to explain th existence outside the radioactive disintegration series of elements whi emit β-rays spontaneously [10]. But that difficulty has been remov since the discovery of artificial radioactivity. Substances that hav been rendered radioactive by artificial means mostly emit β-rays, an usually have a relatively short period of life. For this reason isotope that were rendered active in the distant past by the action of neutron and other suitable agencies in the cosmos are no longer to be foun to-day in terrestrial materials or in meteorites, even by the use of th mass-spectrograph. But in the case of potassium and rubidium, than to the longer periods of life of ^{40}K and of ^{87}Rb, we are at the pres time able to detect measurable quantities of these isotopes.

As a result of the transformation of ^{40}K the chief isotope of calciu ^{40}Ca will be produced, just as the disintegration of ^{87}Rb results i the production of the isotope ^{87}Sr of strontium. This will be clear if w recall that the emission of a β-particle increases the nuclear charge b unity, so that from potassium ($Z = 19$) the element calcium ($Z =$ is produced, and from rubidium ($Z = 37$) the element stronti ($Z = 38$). On the basis of these results, it was to be expected that calci would accumulate in potassium minerals and strontium in rubidiu minerals in the course of geological time. It is worthy of note that so far as evidence is available on this point, it lends support to th conclusion that ^{40}Ca, at least in part (cf. p. 124), is the product resu ing from the disintegration of potassium, and we have already se that ^{87}Sr is the product of the disintegration of rubidium.

Since the β-radiation of rubidium is distinctly softer than that potassium (see previous table), it would appear that an eventu β-radiation from caesium might have escaped detection, in consequen of its still greater softness and feeble intensity. It can be asserted w confidence, however, that the total ionization which might be produ by caesium (inclusive of eventual α-rays) has a value less than $\frac{1}{10}$ th of rubidium, the corresponding total ionization in the case of sodi being certainly less than $\frac{1}{50}$ that from potassium.

Samarium is the only element outside the radioactive disintegrati series that emits α-rays [11]. These have a range of $1 \cdot 15$ cm. at 15 and 760 mm. Hg. One gram of samarium emits 88 ± 5 α-partic per second, and is accordingly 270 times less active than one gr of uranium. The half-value period of samarium ($1 \cdot 02 \times 10^{12}$ years) giv in the table has been calculated on the assumption that, in the cou time. all the atoms of samarium take part in the disintegration process. Presumably only one of the 7 known isotopes of samarium emits α-particles, but it is not yet known which one is responsible. In order to obtain the true half-value period of the radioactive type of samarium, it will be necessary to multiply the above half-value period by the concentration of the active component in the mixed element samarium.

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XXIV

EFFECTS OF THE RAYS FROM RADIUM

THE effects produced by the rays from radium may be grouped in th following way: 1. Photographic Action; 2. Ionization; 3. Excitation Luminescence; 4. Development of Heat; 5. Chemical Effects; 6. C loido-chemical Effects; 7. Biological and Therapeutic Effects; 8. Mec nical Effects; 9. Atomic Disruption.

1. Photographic Action

We mentioned in the Introduction (p. 1) that the rays emitted radioactive substances exert a similar action on a photographic pl to that produced by ordinary light; after development, the plate comes blackened where the rays have been incident. When radioacti research was in its infancy, and before the methods of measurem based on the ionization of air had been developed, the photograph plate was the main instrument used in the study of the new phenome and even to-day it is by far the most suitable piece of apparatus certain experiments. Thus, in experiments on X-ray spectra it h been found that photography enables us to work in a much simpler more exact manner than with ionization chambers, which were orig ally used. Likewise, the 'spectra' of β-rays, obtained by deflexion magnetic field, are best registered on a photographic plate (cf. Fig. Plate I). It can also serve the purpose of enabling us accurately to fol the tracks of α-particles. If we place the point of an activated nee in contact with a photographic plate and allow it to act for a short ti we find on development a very tiny blackened patch on the pl which appears under the microscope as a number of resolved ra tracks, consisting of a series of silver grains. They are caused by α-rays which have traversed the outermost film of the plate at gra incidence. The rectilinear tracks of α-rays can also be detected in way, as well as with the help of cloud-chamber photographs (cf. p and 32). Under favourable circumstances as many as 20 silver gr may be rendered capable of development by an α-particle of 7 cm. ra so that the number of impacts with silver particles in the plate is This follows from the fact that it has been possible to show that ev grain struck by an α-particle is capable of development, whereas on average 6 to 8 β-particles are necessary to make a silver halide nu capable of development. The blackening caused by α-rays is pro tional to the product of the intensity and the exposure time, so Bunsen and Roscoe's relation can be applied to determine the inten

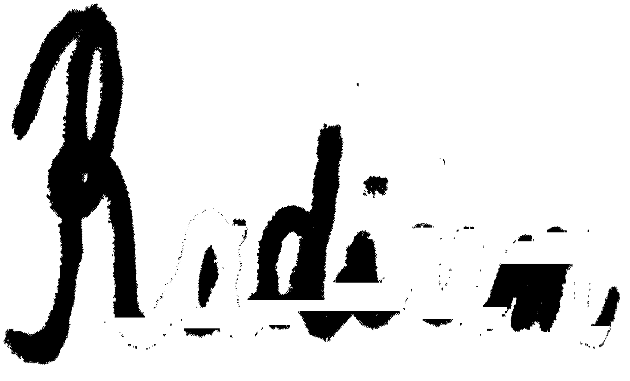
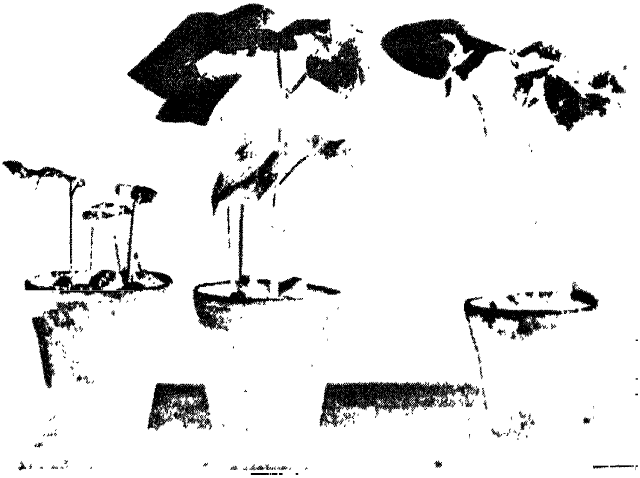


FIG 49 (p. 241). Writing on a Photographic Plate by means of Radi



(*a*) (*b*) (*c*)

FIG. 51 (p. 259). Action of Radon on Shoots of *Phaseolus multifl*
[(*a*) Effect of a large quantity of radon; (*b*) Effect of a small quant
of radon; (*c*) Control specimen, without radon.]

the radiation from the degree of blackening produced. In mineralogy it is often useful to be able to establish the position of a radioactive inclusion in a mineral; a photographic plate laid on a thin section of the mineral will reveal even the smallest active inclusion, provided the experiment be carried out over a sufficient length of time. In the chapter on 'Radioactive Indicators' we have also mentioned an example (p. 175) in which the photographic plate is able to achieve more than the ionization chamber. Nevertheless, the sensitiveness of the photographic method, say for the weak β-rays from radium, is distinctly smaller than that of electroscopic measurements.

Since β- and γ-rays are able to pass through solid substances, in a manner dependent on the density of these substances (see pp. 39 and 51), the possibility suggests itself of producing radiograms by means of radium rays, similar to those produced by X-rays. They are, however, much less suitable for this purpose. In the case of the β-rays the reason is to be found in the fact that, in consequence of marked scattering effects, the edges of the objects radiographed always appear blurred; but even if we deflect the β-rays by means of strong magnetic fields, so that only the γ-rays strike the photographic plate, the radiograms obtained will still be worse from the photographic viewpoint than those obtained by X-rays, because, owing to the greater penetrating power of the γ-rays, the contrasts between the radiographed objects of greater and lesser density are smaller. γ-radiograms are of service, however, in the examination for flaws of large metallic objects, too thick for the application of X-rays.

The length of exposure necessarily varies within wide limits, depending on the strength of the radioactive substance. Fig. 49 (Plate V) shows writing which was obtained by using a preparation of 40 mg. of radium enclosed in a glass tube. This served as a pencil, and was drawn slowly to and fro over the photographic plate, which was wrapped in black paper. The β-rays from the preparation were almost exclusively responsible for the effects in this experiment.

At those places on the gelatine film that are most strongly bombarded by α-particles indentations occur; the swelling capacity of the gelatine is reduced. Moreover, marked solarization effects are observed on those parts of the plate that have been subjected to the action of strong sources of α-rays. When the duration and intensity of the action of the rays on the photographic plate exceed certain values, it is found that the plate is blackened even before it is developed.

2. Ionization

This action of the rays from radium has already been described (p. 7 et seq.), and we have seen that the ionization of the air forms the basis of the whole of the technique of radioactive measurements. It may added, however, that solid and liquid dielectrics also become condu under the influence of the rays from radium, in a similar manner gases. The behaviour of hexane, a liquid hydrocarbon with the form C_6H_{14}, is of interest; the ions produced in this liquid show the us mobility of electrolytic ions, but since the number of ions produ in unit time is only small, the phenomenon of the saturation curr manifests itself here also, just as in the ionization of gases (cf. the footnote on p. 10). We may assume that the small conductivity alw shown by hexane is to be attributed wholly or in part to the actio the natural penetrating radiation (see p. 278).

It has also been shown that the conductivity of pure water increa under the action of the radiation. But in this case it is not quite cert whether we have here an actual increase in the conductivity of the wa itself, or whether the rise is due to the solution of some of the mate of the walls of the vessel under the action of the rays, and the consequ addition of a trace of an electrolyte. In view of the extreme sensiti ness of water towards small amounts of impurity, the latter possibi cannot very readily be excluded.

The ionizing action of the rays from radium is sometimes also u in other physical measurements apart from radiological ones. this means, for instance, we can investigate the contact poten between metals. Moreover, it is of especial use in measurement atmospheric electricity, where we can replace flame electrodes by io ing discs activated with, say, polonium, in order to measure the pot tial of the surrounding air.

3. Excitation of Luminescence

The rays from radium, themselves invisible, are able to excite stances to emit visible light, as already briefly mentioned on p This is most strikingly manifested in the case of the phenomeno *autoluminescence.* Thus, when we subject a barium salt contai radium to fractional crystallization, the mixed barium and radium becomes self-luminous in the dark when the concentration of radiu the mixture has reached a certain value. The colour depends on relative proportion of radium to barium present in the mixture. can, in fact, serve for the approximate estimation of the radium con of the preparation. When a 100 per cent. preparation of radium chlo is fused and thus completely freed from water, it emits a bluish l which is so intense that it can be seen even in bright daylight. Invest tions of the spectrum of this light have shown that it consists of the spectrum of nitrogen. Correspondingly, the helium lines are obta in an atmosphere of helium. The phenomenon of self-luminesc (i.e. really the excitation of fluorescence in the neighbouring gas) has also been observed with strong solutions of radium salts, and with strong preparations of polonium, ionium, mesothorium, and actinium. With weak preparations we can obtain the phenomena of luminescence only by bringing them near to substances which possess marked fluorescent properties. As is well known, barium platino-cyanide ($BaPtCy_4+4H_2O$), zinc blende, and zinc silicate are very suitable for this purpose. The first is used particularly for the detection of X-rays, and likewise for γ-rays, whilst the last two show the phenomenon of 'scintillation', and enable us to detect the incidence of individual α-particles. Each α-particle gives rise to a single flash of light when it strikes a screen coated with powdered zinc blende, and by suitably choosing the strength of the α-ray preparation, we may observe, particularly with a lens, a highly characteristic phenomenon—the luminous field appears to be in a state of agitated motion, as a result of the ever-changing incidence of individual luminous points. This apparatus can be made very simply, and is known as a 'spinthariscope'. The duration of an individual flash of light is only 10^{-4} seconds.

Special precautions are necessary for the preparation of samples of zinc blende which fluoresce satisfactorily. The amorphous ZnS powder obtained by precipitation from an aqueous solution does not show phosphorescence, but it can be transformed into the crystalline form by heating to redness. Before the precipitation we must either ensure the presence of an excess of the zinc salt, or we must add a foreign heavy metal like copper, because even the crystalline blende is capable of phosphorescence only when 'nuclei' are available (see below). The far-reaching conclusions resulting from the fundamental investigations on the scattering of α-particles and on the disruption of atoms were based initially on the appearance of a few flashes of light on zinc sulphide screens, in unexpected directions and at unexpected distances. This emphasizes the great importance which attaches to the preparation of good zinc sulphide screens for scientific work.

Preparations of zinc sulphide with which a certain quantity of a radioactive substance has been mixed are of practical importance, for they exhibit a more or less permanent luminescence, which is independent of external sources of energy. These radioactive 'luminous substances' differ from the phosphorescent substances formerly used, in that they do not require previous illumination before they luminesce. They are used for coating the pointers and figures of clocks, watches, and compasses, and for rendering visible such things as signs (e.g. in theatres), bait on fishing-hooks, and so on. The most rational α-rayer to use for this purpose is radiothorium, since the luminescing power of every zinc sulphide preparation appreciably diminishes even after the lapse of a few months. For this reason there is no special poin using long-lived substances like radium or mesothorium, altho radium is at present less expensive than radiothorium. In prac one gram of zinc sulphide is mixed with a quantity of a material, the intensity of the γ-radiation from which is equivalent 10^{-4} to 10^{-1} mg. of radium. When a good sample of zinc sulphid available, several per cent. of the energy of the α-rays is transform into light, and this is fortunately distributed for the most part the visible spectrum, with a maximum at 550 mμ (see p. 30).

The above-mentioned diminution with time of the luminescing po of preparations of zinc sulphide is most probably to be explained the assumption that the luminescence originates in the 'centres' nuclei that are postulated in all 'phosphors'. In zinc sulphide t centres are present presumably only in relatively small numbers, al one in every thousand ordinary molecules, and they are gradu destroyed by the action of the radiations from the radioactive stance.

Apart from barium platino-cyanide, zinc blende, and zinc sili a large number of substances fluoresce more or less strongly under action of the rays from radium; thus the mineral willemite (Zn_2S emits green light, kunzite (a silicate of lithium and aluminium) e red light†, scheelite ($CaWO_4$) fluoresces brilliantly and diamond n less strongly, both emitting blue light. With these last two stances scintillations can also be observed when α-particles are inci upon them. Moreover, most benzene derivatives luminesce under action of the rays from radium, particularly those with many rings the derivatives of salicylic acid, e.g. salipyrin (= acid salicyl-antipy Furthermore, the crystalline lens, the vitreous fluid, and the reti the eye fluoresce under the action of γ-rays; this is the reason why blind persons, provided the retina and optic nerve are not dam are able to experience the sensation of light when a radium prepar is brought near their eyes. In such experiments great care shoul exercised, owing to the possibility of physiological damage being to the tissues by the rays from radium (see § 7).

Most fluorescing substances become coloured under lengthy exp to the rays, but simultaneously the fluorescence diminishes and 'fati occurs. This fact is both of practical and of theoretical interest. heating, often only slightly above room temperature, or by illum tion with light, the colouring can frequently be annulled, and a same time the ability to fluoresce restored. This decoloration by n of heat or light is generally accompanied by luminescence and the emission of electrons (thermoluminescence and photo-electric effect), as, for instance, with kunzite, the original rose colour of which is changed to green by the rays, or with fluorspar, which is transformed from a green to a blue colour by the action of the rays. New vessels and tubes of glass luminesce much more strongly under the action of radioactive solutions or gases than those that have been in use for a long time: this is a striking illustration of the fact that glass fatigues or loses its ability to fluoresce when subjected to the action of the rays. Glass apparatus that has been exposed to the rays for a long time always has a brown or violet colour (see p. 248), and also shows very clearly the phenomenon of thermoluminescence (with the well-known characteristic green glow of X-ray tubes). Quartz that has assumed a violet colour also shows the same luminescence during its decoloration by means of heat.[†]

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† Kunzite, and in a lesser degree also fluorspar and a few other crystals, can be to show luminescence very strongly when they are first rayed by γ-rays and late ordinary light.

The close connexion between the phenomena of luminescence and colour changes can be readily understood from the theoretical point of view. Detailed investigations in this field have been undertaken with various salts, but primarily with natural rock salt, and they have led essentially to the following result. When NaCl is coloured by 'illumination' with β- or γ-rays, the primary process consists in the absorption of a quantum of radiation by a chlorine ion, whereby the superfluous electron responsible for the negative charge of the chlorine ion is removed and transported to one of the neighbouring positive Na-ions. The latter is neutralized in this way and transformed into an atom of sodium, which has the ability to absorb visible light. The resulting colour will depend on whether and how strongly the discharged sodium ions (i.e. atoms) are influenced by lattice forces; if they are freely mobile and unite to form larger complexes, a process which is favoured by a moderate rise of temperature, they then absorb yellow light in the neighbourhood of the *D*-line, as we should expect from theory, and the rayed rock-salt assumes a blue-violet colour.[‡] By means of experiments on the influence of pressure applied to one side of the crystal it has been possible to show that the process above described takes place especially at disturbed places in the crystal lattice. For the same reason alkali chlorides that have been crystallized from a fused mass are more susceptible to colour changes than are the more regularly crystallized.

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[*] Thermoluminescence and 'phosphorescence' cannot be sharply differentiated: thus doubly refracting calcspar that has been coloured yellow phosphoresces with emission of red light even at ordinary temperatures.

[‡] The often noted agreement in the colour of rayed salts with that of their colloidal aqueous solutions (sols) is also based on a separation of the metal of this nature; thus, under the influence of the rays from radium, borax beads to which a little lithium has been added become brown, with sodium they become violet, with potassium blue, and with rubidium greenish blue, and these are just the colours of the corresponding sols.

salts obtained by crystallization from solutions. When the ra process is interrupted and the coloured salt is heated, the val electron of the sodium atom returns to the chlorine atom, whereby ionic lattice is reformed and decoloration takes place. This retur the electron can give rise to the emission of light in different ways on these lines it is possible to explain the thermoluminescence prod by heating coloured salts and glasses. The phenomena of the emis of electrons, decoloration by the action of light, and in particular the feeble fluorescence of strongly coloured glasses all find a satisfac explanation within the framework of this theory, but we shall not cuss them in further detail here.

4. Development of Heat

The following details will serve to amplify the information alr given on p. 1.

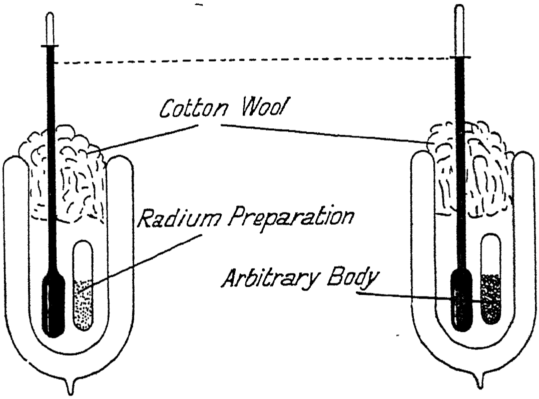

FIG. 50. Heat Development of a Radium Preparation.

A simple experimental arrangement that enables us to demons the continuous liberation of heat by radium preparations is repres diagrammatically in Fig. 50. A radium salt contained in a glass is situated in the left of two identical Dewar vessels, each pro with a thermometer, and in the right-hand vessel is a similar containing the same quantity of a barium salt. The temperat the left-hand vessel is always found to be somewhat higher than i right-hand vessel. If the salt introduced contains half a gram c element radium, the difference in temperature may amount to as as 5° C., and is only limited by the magnitude of the unavoidabl of heat to the exterior. Correspondingly, the mercury thread Bunsen ice calorimeter, by means of which the amount of ice n per unit of time is measured, moves constantly with uniform velo The amount of heat is generally determined quantitatively by ev ing the amount of electrical energy which produces the same quantity of heat as the preparation concerned (method of compensation). In setting up the experiment, of course, care must be taken to ensure that all the rays emitted are absorbed within the calorimeter, with the exception of a fraction of the γ-rays, for which a correction can be applied. In this manner it has been found that 1 gm. of radium in equilibrium with its short-lived disintegration products develops 140 calories of heat per hour, or enough to heat more than the same mass of water from 0° C. to 100° C. In accordance with the slow transformation of radium into the end-product lead, this generation of heat gradually diminishes. In the time required for 1 gm. of radium to decay completely (roughly 25,000 years) it must evolve $3{\cdot}4 \times 10^9$ calories; for purposes of comparison it may be mentioned that we should have to burn about half a ton of coal in order to produce this quantity of heat. Even the transformation of 1 gm. of oxy-hydrogen gas into water only develops about a millionth part of the above amount of heat, viz. 3,700 calories, and it is well known that this reaction is associated with a heat of combustion which is unusually high for chemical changes.

The following consideration gives us information as to the origin of the large quantities of heat generated by radioactive substances. From the velocity and mass of the α-rays and recoil rays, and from the energy of the β- and γ-rays, which is likewise known, we can calculate the total energy liberated by the preparation in the form of rays. For complete absorption of the rays, this energy must be transformed into heat. In this way we obtain for the amount of heat resulting solely from the absorption of the rays from 1 gm. of radium, together with its disintegration products, the value 140·1 calories per hour; of this amount 124·4 calories are produced by the α-rays and the recoil rays, 6·3 calories by the β-rays, and 9·4 calories by the γ-rays. Since the quantity of heat found experimentally agrees with this value within the limits of error of experiment, we must conclude that the heat developed by radioactive substances is due to the energy of the rays, and not to any additional inter-atomic processes.

By means of sensitive apparatus it can also be proved that polonium and even thorium and uranium are sources of continuous development of heat, exactly as we should expect from the disintegration theory. One gram of uranium in equilibrium with its disintegration products generates about 9×10^{-5} calories per hour. Information on the calorimetric detection of mesothorium in radium is given on p. 56.

5. Chemical Effects

(*Note.* The study of the chemical effects of the rays from radium is sometimes called 'radio-chemistry' in the narrower sense, just as the designation 'photo-chemistry' is applied to the study of the chem effects produced by light. Throughout this book, however, we confine the use of the term 'radio-chemistry' to the chemistry of radio-elements, or the study of their chemical properties and reacti since no other short name is available for this much greater and more important branch of the science.)

It has already been mentioned that many similarities exist bet the chemical effects produced by the rays from radium and t produced by light. In our discussion of the ionization in gases we ciated it with the better-known case of electrolytic conduction. It serve a useful purpose if, both in the individual examples and in theory of the phenomena of the chemical effects of the rays from rad we likewise always draw attention to the analogous photoche effects. We shall first discuss a number of experiments on the che changes brought about by the action of the rays from radium.

(*a*) *Chemical Effects in Solids*

Colourless glass becomes coloured under the action of the rays radium; ordinary sodium glass and glass containing manganese be violet, whilst glass containing iron or potassium becomes brown. coloration is annulled by the action of light, and still more quick the action of heat, and at the same time the phenomena of lumines already mentioned make their appearance (see p. 245). Precious s and minerals also alter in colour; diamond is transformed superfi into graphite, blue sapphire becomes yellow (synthetic sapphires re unchanged), bright green fluorspar becomes dark blue, red ku green, and colourless rock-salt blue or brown. Pleochroic haloes are to be seen in many minerals (see p. 269), and which are a conseq of radioactive inclusions, show the same colorations as can be pro by artificially raying the same minerals. It is well known that glasses assume a yellow, green, or violet colour also when the subject to the action of light for a long period of time, or when t tensity of the radiation is large.

In the case of pleochroic haloes we have a particularly st example of the great similarity between the action of α-rays and p chemical processes. In the vicinity of the dark rings the mica is times more transparent to light than in places that have not affected at all by α-rays [1]. Quite a similar phenomenon c observed in photographic plates near to regions that have been st blackened ('Eberhard Effect').

One of the best-known photochemical effects is the bleaching of An analogous destruction of the colour by means of the rays radium can also be detected with, say, indigo or chlorophyll.

ations are more obvious in solutions or with strips of material soaked the solutions than when the dye is in the compact solid form.

It is well known that light exerts a destructive action on paper ntaining lignin, in the presence of air. The rays from radium exert much more energetic destructive action on every kind of paper, on lk, linen, celluloid, and the like. The action is here probably due to idation by the ozone produced by the rays. In a similar manner, araffin wax, vaseline, and rubber become hard, and tap-grease is ecomposed with evolution of CO_2 by the action of the rays. These henomena must be taken into consideration in the construction of paratus for radioactive purposes.

Yellow phosphorus is transformed into the red variety under the tion of light; exactly the same effect has been observed with the rays om radium. When light is incident on selenium the electrical resistance f the selenium is found to diminish, and this fact is the basis of many rocesses, such as light-telephony and the ignition of explosives from a distance. The resistance of selenium also diminishes when the rays om radium are incident upon it. Nitrogen iodide explodes instantaneously when subjected to the light from burning magnesium; about 20 conds are required before the explosion takes place when the nitrogen odide is submitted to the α-radiation from 3 millicuries of radon at a stance of 1 cm. During this period some 10^7 or 10^8 α-particles impinge n the nitrogen iodide.

Finally, the reducing action of the rays from radium on silver chloride and silver bromide is also of great importance, and quite analogous to he action of light. It constitutes the basis of the photographic action f the rays, and for this reason it has already been mentioned on p. 240.

Chemical Effects in Liquids

The decomposition of water under the influence of the rays from dium is of especial importance. In this process, gases consisting of H_2, O_2, and O_3 are liberated, and simultaneously a little hydrogen eroxide is formed in the water. We can picture the processes by means f the following two equations:

$$2H_2O = 2H_2+O_2,$$

hereby some of the O-atoms initially formed go to form ozone with the O_2, and

$$2H_2O = H_2O_2+H_2.$$

Most of the decomposed water molecules follow the first reaction, and so form oxy-hydrogen gas, but owing to the second reaction there is ways an excess of hydrogen mixed with it. The amount of the ecomposition products obtained from a given quantity of a dissolved

salt of radium depends first on the fraction of the α-, β-, and γ-
absorbed by the water, and thus on the dimensions of the contai
vessel, and, secondly, it depends particularly on the magnitude o
gas space over the liquid, because this determines the relative dist
tion of the radon between the liquid and the gas phases (cf. p.
As an approximate estimate, it may be stated that a daily produ
of 20 c.c. of gas has been observed from 1 gm. of radium in solutio

This continuous evolution of appreciable quantities of oxy-hydr
gas can give rise to much trouble when radium preparations are s
off in glass tubes before being completely dry. The pressure of the
developed may burst the tube, and a slight and sudden applicati
heat may result in a veritable explosion. For this reason it is absol
necessary, before sealing off strong preparations, to maintain the
a temperature of over 100° C. for several hours.

If only the penetrating rays from radium are used for the decom
tion of water, the velocity of decomposition is very much small
when the radium preparation is enclosed in a double-walled
filled with water. It can be increased by enclosing the outer ves
a sheath of lead. In this case secondary β-rays are emitted by the
and since they are absorbed by the water more strongly than the pri
γ-rays, they give rise to a bigger effect. This experiment has
mentioned because it presents a certain formal analogy to wh
called 'optical sensitization'; thus a photographic plate becomes
tive to red rays when it contains eosin, and after the addition of ch
to a mixture of hydrogen and oxygen the last two gases combi
virtue of those rays that are absorbed by the chlorine, whereas i
absence of chlorine the action of visible light is only a slow one.

The decomposition of water by the two reactions mentioned
can also be brought about by means of light, particularly by
violet light.

It has been mentioned that a certain proportion of hydrogen pe
is formed from water under the action of the rays from radium.
reverse reaction, the decomposition of hydrogen peroxide, is
markedly influenced by the rays. Ultra-violet light produces the
effect; in fact, a mercury lamp acts incomparably more quickl
even a strong preparation of radium.

From amongst other reactions that take place in liquids, it m
mentioned that in the mercury oxalate actinometer oxalic a
decomposed by the rays from radium as well as by light:

$$2HgCl_2+C_2O_4(NH_4)_2 = Hg_2Cl_2+2CO_2+2NH_4Cl.$$

The amount of calomel precipitated, or the amount of carbon d
liberated serves as a measure of the intensity of the light.

reactions that have been described are also in complete qualitative agreement with the transformations wrought by light, but in general they take place several hundred times more slowly than when a mercury lamp is used as the source of light. The following are examples of such reactions: the liberation of iodine from a solution of iodine in chloroform; the decomposition of liquid HBr or an aqueous solution of HBr, or of HI or KI solutions; the precipitation of silver from dissolved silver nitrate; the decomposition of nitric acid into nitrous acid, nitric oxide, and oxygen.

The observation that platinum vessels are attacked by solutions of radium chloride is explained by the liberation of nascent chlorine, which in its turn dissolves the platinum.

Chemical Effects in Gases

The most striking of these is the formation of ozone from oxygen: the characteristic smell of ozone is detectable in the proximity of every preparation that is emitting intense radiation. In consequence of this, metals like lead, mercury, and aluminium, and also paper, linen, and the like (see above, p. 249), are oxidized in a longer or shorter interval of time when they are situated in the neighbourhood of radioactive preparations. In particular, the formation of ozone has also been accurately investigated quantitatively, but we shall defer details of this work until we discuss the theory of the chemical action of the rays (see p. 255).

Mention should be made of a few other reactions in gaseous systems that have been studied in some detail. They include the oxidation of hydrogen, carbon monoxide, and various hydrocarbons (methane, ethane, propane, and butane); the decomposition of carbon monoxide, ammonia, hydrogen chloride, hydrogen bromide, and nitrous oxide; the synthesis of water, ammonia, and hydrogen chloride; the polymerization of acetylene, cyanogen, and hydrogen cyanide. The photochemical processes corresponding to these changes are so well known that it is hardly necessary to consider them in further detail here.

Under the influence of radiation, nitrogen also becomes more reactive: a diminution in pressure due to the influence of α-rays has been observed in glass flasks filled with pure nitrogen, and having various substances Na, K, S, P, I, As, Mg, Hg) on their inner walls.

d) General Nature of the Chemical Reactions produced by the Rays from Radium

We have not classified the reactions referred to above to indicate whether they are caused by α-, β-, or γ-rays, because in many cases details on this point are not available, and in most of the cases in which the parts played by the different kinds of rays has been studied i been found that all three produce the same changes. In general we say that the α-rays have the strongest action, if this is not prevente their ready absorbability. Most reactions with gases have been ca out with radon, in which case the major part of the action can cert be ascribed to the α-rays; this also holds for the decomposition of w into oxy-hydrogen gas, which has also been established by the u polonium, a pure α-rayer; likewise for the breaking up of nitr iodide. For this reason small quantities of radioactive substances bring about colorations in glass only to a depth of a few hundredt a millimetre, corresponding exactly to the phenomenon of pleoc haloes (see p. 269), in which the β- and γ-rays emitted simultane with the α-rays also have no appreciable action.

In other reactions the β-rays are mainly responsible for the cha for they are able to penetrate more deeply by virtue of the fact they are corpuscular rays and may possess considerable energy particular, in the separation of iodine from iodoform in benzene. appear to be quite ineffective. Like ultra-violet light, β-rays decom water into hydrogen peroxide and hydrogen, in contrast to α-ray

The absorption of the γ-rays is so small that their quantitative cannot be large, owing to the small losses of energy involved (cf. p on the sensitization for γ-rays). In spite of this, they are the only which call for consideration from the viewpoint of deep-seated v effects; this is the basis of their prevalent application in medici

From the illustrations that have been mentioned it is clear that, in solids and in liquids and gases, the chemical actions produc the rays from radium are extraordinarily similar to those of lig least in their outward manifestations. Many reactions are quite i cal, and this is particularly true of those reactions caused by the trating rays, in which case the radioactive preparation used i experiment is enclosed in a glass tube. From the theoretical view this agreement can be readily understood, for the γ-rays are n else than light of very short wave-length. When the more r absorbable rays are also admitted, the effects are very much str but even then they are in all probability not different qualita from those produced by light. Nevertheless, reactions like th nounced formation of ozone take place under such conditions q and to an appreciable extent, although they would hardly be perce by the use of light. It should be particularly emphasized that decomposition of ammonia by α-rays an alteration of the press an addition of foreign gases (N_2, H_2, N_2H_4) exerts a very influence, even quantitatively, to that observed in the case of chemical decomposition [2].

A further similarity with photochemistry is embodied particularly in the fact that one and the same reaction is often favoured in both directions. But whereas in the case of light, as with hydrogen bromide, it has been established that different wave-lengths produce opposite effects, such a differentiation has not hitherto been observed when the rays from radium are used. Thus radon decomposes water, and at the same time brings about the combination of oxy-hydrogen gas; an analogous behaviour is found with ammonia. It is sometimes regarded as surprising that in certain cases light produces effects the reverse of those due to radium rays, as when colorations in minerals due to the latter rays are made to disappear under the action of illumination by light. But when we remember that the effects produced by different kinds of light are often opposed to one another, we can hardly doubt the essential similarity between the processes effected by light and by the rays from radium.

Of especial importance is the fact that the temperature coefficient of the velocity of reactions actuated by the rays from radium is just as small as in photochemical reactions; for the decomposition of hydrogen peroxide it has been found to be 1·2 per 10° C.

Theory of the Chemical Reactions produced by the Rays from Radium

Since the outward manifestations of these reactions and those of photochemistry have been found to resemble each other so closely, we may ask ourselves whether it can be assumed that the mechanism of the changes is also the same in the two cases.

The more recent physical advances on the subject of light quanta and on the connexions between radiation and matter have resulted in great progress being made in the theoretical treatment of photochemical processes. By using thermodynamical principles as a basis, the earlier tendency was to introduce a strict differentiation between those processes which take place by the addition of energy by light and those in which the light accelerates the process in a catalytic fashion. But it has now been recognized that, from this point of view, reactions which run a quite similar course have often had to be treated separately. The mechanism of the processes was first revealed by considering them from the atomistic viewpoint by means of Einstein's 'law of photochemical equivalence'. If we divide the absorbed energy of radiation by the value of Planck's element of energy corresponding to the wave-length used, then by the equivalence law we must obtain the number of elementary processes involved in the experiment. In point of fact, it is found, say when oxygen is subjected to ultra-violet radiation, that the number of elementary processes calculated in this manner is of the same order of magnitude as the number of molecules of ozone formed. To be more exact, twice as many molecules of ozone are formed, and h we may assume that in every elementary process one O_2-molecul split up, and the resulting 2O combine with two additional O_2-mole to form $2O_3$.

It is necessary at this stage, however, to recall that, in spite o essential validity of the law of photochemical equivalence, nume instances of photochemical reactions are known in which the am actually converted are found to be smaller and sometimes greater t those which correspond to the number of the elementary proc calculated, for it is not the elementary processes themselves w are observed but only the chemical changes brought about by t In certain circumstances a fraction of the absorbed light quanta increases the thermal content of the substance instead of contrib to chemical change, and in this case the chemical yield must lag be the yield calculated. On the other hand, an elementary process be immediately succeeded by a 'chain reaction', and then the am of chemical change may be enormous, and even more than a mi times greater than would correspond to the law of equivalence. It suffice to recall the well-known case of a mixture of chlorine and hy gen. Each absorbed light quantum breaks up a molecule of Cl_2 its constituent atoms; each free atom of chlorine is able to form by uniting with an H-atom from an H_2-molecule and to set at li the other H-atom; this free H-atom can in turn react with Cl_2 to a molecule of HCl and liberate Cl, and so the process goes on. In way it is possible to explain why, with a mixture of equivalent am of hydrogen and chlorine, a single quantum of light is able to pro the formation of a very large number of molecules of HCl.

Now if we wish to examine the question as to whether the che reactions called forth by the rays from radium also obey the la photochemical equivalence, we must first adequately appreciate the number of elementary processes is determined not by the nu of primary α- or β-particles fired into the reacting system, but b number of secondary ions produced by these particles. This emerged quite clearly from an investigation on the formation of by cathode rays, which is mentioned here because the mechani this reaction is intimately related to that of the changes brought by the rays from radium. Cathode rays were allowed to enter a containing oxygen, and then determinations were made first o amount of ozone formed, and, secondly, by measurement of the sa tion current, of the total number of ions produced in the reaction Whereas the number of primary electrons projected into the was from a hundred to a thousand times smaller than the numb molecules of ozone formed, good agreement was found betwee number of ozone molecules and the number of pairs of secondary ions produced in the reaction vessel. As we have seen on p. 11, a single electron can give rise to many thousands of ions as a result of ionization by collision, and it is obviously these ions of secondary origin that give rise to an equal number of chemical elementary processes in accordance with the law of photochemical equivalence.

Reverting to the case of the rays from radium, it is necessary to apply an exactly corresponding calculation of the number of electrons taking part in the reaction. Here also it is a question of a dependent electrical conductivity caused and sustained by an outside ionizing agency, and the number of ions contributing to the conduction of electricity is much greater than the number of primary particles entering the gas, the former number sometimes being as much as 10^5 times the latter (cf. p. 27). Now the total number of pairs of ions produced by a radium preparation of definite strength can readily be found from the saturation current. In the formation of ozone from oxygen under the action of the rays from radon it was thus possible to compare the number of molecules of ozone formed with the number of pairs of ions produced, and when this was done it was found that the requirement of equivalence was excellently confirmed within the limits of experimental error. Here also we should obtain much too small a value for the number of elementary chemical processes if we were to regard the charges carried by the primary α-particles fired into the gas as being the determining factor in the reaction, instead of those of the pairs of secondary ions formed.

This equivalence between the number of molecules entering into chemical reaction and the total number of ions formed by the α-rays has been proved not only for the formation of ozone, but also in the formation of water, ammonia, and hydrogen chloride from the constituent elements, and also in the decomposition of ammonia, hydrogen chloride, hydrogen bromide, and carbon monoxide. Moreover, it has also been established in liquid systems, as in the decomposition of water, liquid hydrogen bromide, and in an acid aqueous solution of potassium iodide. In accordance with this equivalence it has been possible to show that a definite amount of chemical change is associated with the presence of a definite number of ions, in a similar manner as in Faraday's law. In contradistinction from Faraday's law, however, these ions do not participate in the transport of current, and hence in this case we generally speak only of an 'iono-chemical equivalence'.

Chemical actions are here brought about in a roundabout way by the formation of excited atoms or of ions. The recognition of this fact renders it intelligible why the utilization of the radiative energy in its transformation into chemical energy is such a poor one, both with light

and with the rays from radium, assuming the validity of the sin
law of equivalence, but not in the case of chain reactions. On
assumption that the first step in the process is complete ionizat
$5{\cdot}5\times 10^{-11}$ ergs must be involved in the formation of a pair of ion
air. Now if one such pair of ions induces only one molecule to take
in chemical change, the greatest known heat of reaction in suc
transformation, which we shall regard as a measure of the free ene
amounts to no more than 7×10^{-12} ergs. Hence only about 13 per c
of the energy can be stored up in the form of chemical energy. M
over, since usually more than one pair of ions per molecule is necess
and the heat of reaction is smaller than the above amount, it fol
that the utilization of the energy is in general still worse (2 to 3
cent.).†

It is particularly noteworthy that the iono-chemical law of equival
also holds when the chemical reaction takes place in the directic
the free energy, so that here also a much greater radiative than chem
energy is involved. It makes absolutely no difference in the numb
ions required that now no chemical energy whatsoever must be st
up; the large thermodynamic difference does not make itself man
and from this we must conclude that even in such cases we may
conceive the action of the rays to be of a catalytic nature (cf. what
said above on p. 253 about the inadvisability of the older division
two categories). The experiments supply unequivocal evidence tha
effectiveness, say of radon, is of the same order for a reaction w
proceeds in the direction of its own free chemical energy, as for one
proceeds in the reverse direction. This observation is quite simil
that which has been made in the field of photochemistry. Thus i
decomposition of ammonia by means of ultra-violet light it has
established that the same intensity of light is necessary for the de
position of a given quantity of ammonia, no matter on which si
thermodynamic equilibrium we may be.

Finally, work carried out in recent years has revealed that the
kind of chain reactions can be initiated by the rays from radium
light. In the case of an equivalent mixture of hydrogen and ch
it was possible to show that ionization by α-rays gives rise to cha
the same length (a few thousand molecules) as photochemical excit
and that the temperature coefficient of the two reactions is the
The synthesis of phosgene from CO and Cl_2 also gives the same
when the absorbed light quanta are replaced by an equal num
pairs of ions produced by α-rays. Further examples of chain rea
that can be initiated by the radiations from radium are the chlori

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† The calculation comes out more favourably when we do not assume co
ionization as a preliminary to the change, but rather only excitation of an electro

of benzene, and the oxidation by oxygen of sodium sulphite dissolved in water. This last reaction is noteworthy in that it takes place in a liquid system.

From what has been said there can be no doubt that the chemical reactions that take place under the influence of the rays from radium can be interpreted theoretically by the application of the ideas developed in photochemistry. But at the present time the development of a detailed reaction mechanism is faced with considerable difficulties [3].

6. Colloido-Chemical Effects

In this section we shall discuss individual effects produced by the rays from radium, in so far as they are intimately related to questions of colloidal chemistry. It is, of course, not possible to delineate them sharply from the topics already treated. Thus it is known that the photographic process, of which we have previously spoken, must also be considered from the colloido-chemical viewpoint, and the colorations dealt with on p. 245 (second footnote) likewise present certain colloido-chemical problems for solution.

The study of the action of the rays from radium on the stability of colloidal solutions belongs to colloido-chemical investigations in the narrower sense. Here the interesting result has been established that positive colloids are precipitated, whereas negative ones survive the radiation. The experimental arrangement was so chosen that almost exclusively β-rays were effective, and since these carry negative charges, we can understand why they deposit the positive colloids. Thus if we add to a colloidal solution of iron hydroxide a quantity of a salt solution, say sodium acetate, just insufficient to produce a change, we can obtain turbidity of the colloid by means of radium rays, whereas a control sample that has not been subjected to radiation will remain unchanged. With a sol of cerium hydroxide it is not even necessary to sensitize it previously by means of an electrolyte; by subjecting the sol to radiation it is transformed into a coherent gel even after a period of 24 hours, whereas it remains unchanged for years when not submitted to the action of radiation.

None of the electro-negative colloids of gold, molybdenum blue (an oxide of molybdenum containing water), and vanadium pentoxide, the last of which tends to form a gel just like cerium hydroxide, were affected when subjected to radiation. Albumin, which also forms electro-negative colloidal solutions, is deposited in flocculent masses, but it is probable that this is not simply a phenomenon of discharge, but rather due to the fact that the albumin first loses its original nature.

Under certain conditions the rays from radium are also able to bring about the formation of cloud deposition. Thus if we introduce in closed vessel distilled water, a piece of sulphur, and radon, the space becomes filled with a persistent cloudy suspension. Since we detect traces of sulphuric acid in the water, the explanation of t phenomenon undoubtedly seems to be that SO_2-molecules, and fr these SO_3-molecules, are produced by the action of the rays, and th serve as condensation nuclei for water vapour. Visible fumes mu formed in exactly the same way as when, say, hydrogen chlor escapes into the moist air of a room. When sulphur has not b introduced into the vessel, only a very much weaker cloudines obtained. It is probable that in this case the nitrogen oxides form by the action of the rays from the radon give rise to just suffic condensation nuclei to enable a cloud to form, for if we replace the by carbon dioxide, we can no longer observe any permanent cloud.

If we use super-saturated water vapour, condensation occurs direc on the ions formed, without the necessity for chemical reactions. T method is utilized to render visible the tracks of the rays from rad active substances (see p. 19).

The following observation is also more or less closely related to facts already described. By means of β-rays it is possible to incre the rate of crystallization of supercooled sulphur. If only a fract of the sulphur drops are rayed, many more crystallization nuclei be found among these drops than among those that have not been treated.

7. Biological and Therapeutic Effects

Not long after the discovery of radium it was observed that substance must not be handled without precaution. If we allo strong radium preparation to lie for some time on the skin, sores devel which are very similar in appearance to burns. Whereas in the cas the action of heat, however, our attention is immediately drawn to danger by the resulting pain, the rays from radium have the sini property that they do not at first give rise to any unusual feeling: a strong preparation it is not until several days or a week or two l that the inflammatory process begins. Particularly in the earlier d of radioactive research, when the danger had not yet been recogni many radiologists suffered from such sores on their fingers. In s cases a marked atrophy of the affected finger-tips developed, and t is a danger of cancer developing later, just as in the case of b produced by X-rays.

The maximum daily dosage of γ-rays that a human being tolerate without apparent harm is 0·1 röntgen unit (cf. p. 57). W working with radioactive preparations, it is advisable to carry in pocket a miniature ionization chamber about the size of a fountain-pen and charged to a potential of a few hundred volts. By testing the extent to which discharge has taken place in the ionization chamber after the lapse of a few days, it is an easy matter to ascertain whether or not the daily dose of γ-rays to which the body has been subjected has exceeded 0·1 r unit per day.

After it had been established that the rays from radium have a physiological influence, it was suggested that they might have an application in medicine, and as a matter of fact it is possible to produce satisfactory improvement in various skin diseases, whereas healthy skin is damaged by the rays. The penetrating rays often have a healing or at least a favourable and soothing effect on internal diseases, particularly in cases of carcinoma. In most cases normal tissue is from four to seven times more resistant to the effect of the rays than diseased tissue. Moreover, much success has been attained in cases of gout and rheumatism, and science has recently been inclined to attribute the healing action of many natural springs to their content of radon. When baths are taken in water containing radon, the process involved is probably that the radon is given off by the water, and inhaled by the patient (see p. 226). A decrease in the leucocyte content of the blood has been observed as a result of the injection of radioactive solutions, and it may be possible to make use of this fact in cases of leucaemia.

The underlying processes are not only of great importance in medical therapy—on which subject further information can be obtained from the extensive literature of medical radiology—but they are also of undoubted interest from the viewpoint of theoretical biology, in which connexion they have frequently been investigated. We can discuss here only the most important of the experimental results.

Stimulants which are harmful to an organism when administered in large doses often have a favourable influence when used in small doses. Here we may recall the fatal action of large quantities of many compounds used in medicine. Now this general rule, which has occasionally been designated a 'fundamental law of biology', has been completely vindicated in its application to the influence of the rays from radium. Young plants exposed to the rays from radium are found to exhibit a distinct improvement in their growth when only small doses are used, whereas large doses are highly detrimental to the development of the plants, as can be seen from Fig. 51 (Plate V). By the action of a sufficiently strong source of radiation we can destroy the vitality of seeds, and kill bacteria (cholera, typhus, anthrax, streptococcus) and also higher animals such as caterpillars. Germ-cells are especially sensitive: if we subject ova or spermatozoa to the action of the rays, we can observe different kinds of developmental arrest. Changes in the cells which cannot be detected even with the highest magnifications mani themselves in the further development by the appearance of deviati from the normal development. A former contention of the specific ac of the rays on biochemical compounds *in vitro* has not been veri On the other hand, β-rays have a marked capacity for haemol action, and this fact may perhaps be made use of in connexion w their application in medical practice.

The danger of 'burning' the fingers, which is considerable wh radium preparations are often handled, can be diminished by use of rubber finger-caps pulled over the ends of the fingers wh actually come into contact with the tubes containing the substa They suffice to screen off the soft β-rays, which appear to be mai responsible for the burns, and they are to be preferred to harder mate because in the latter case secondary β-rays are likely to be produ by the γ-rays incident upon it. But the chief advantage resulting f their use is the absence of any hindrance to the handling of preparati with which one is working, say in transferring radioactive mat from one tube to another, and similar operations. With strong prep tions, however, finger-caps give inadequate protection, and suit forceps should be used. Radium burns are particularly troubles because it frequently happens that even if they mend there remai supersensitiveness of the skin, and the rays from quite a small quan of radium are then sufficient to give rise to renewed inflammation. I we have what is from the theoretical point of view a very interes case of 'indirect' or 'physical anaphylaxis'; the anaphylactogen not directly introduced into the organism as in ordinary anaphy (e.g. as a foreign type of albumin), but are formed in the organis the action of the rays.

Biologically, neutrons are roughly ten times as effective as X- in respect of the change they bring about in the blood picture of a The maximum permissible daily dosage of neutrons is estimated t one-tenth that for γ- or X-rays, or $0{\cdot}01\,r$ unit (cf. p. 258) [4].

An important biological effect of γ- and of X-rays is the increase duced by them in the rate of mutation of genes. All types of mut occur, including spontaneous ones, but no types are observed w are specific to the rays. The rate of mutation is found to be indepen of the wave-length of the rays and to depend only on the total am of the incident radiation. The interpretation of these results see be that one direct 'hit' suffices for the initiation of mutation by X and by γ-rays, and that this hit consists in the formation of a p ions. Various speculations have been made, according to whic cosmic rays (see p. 278) are held responsible for the production o types, but these lack experimental support.

8. Mechanical Effects

The mechanical effects are always brought about indirectly by electrical or by chemical processes. Thus, when it was observed that glass tubes into which radium had been sealed exploded, the cause of this was to be found in the excessive pressure brought about by the development of oxy-hydrogen gas (see p. 250). The assumption of electrical discharges, which have sometimes been held responsible for this effect, appears to be quite superfluous. Quartz tubes in which strong radium preparations have been kept develop a very characteristic meshwork of fine cracks.

The 'radium clock' provides a pretty experiment for demonstration purposes, and illustrates how the rays from radium may be utilized indirectly to give rise to motion. It consists of a small glass tube containing radium, supported on an insulating quartz rod inside a somewhat wider evacuated glass tube, and having attached to its lower extremity two electroscope leaves. Since the β-rays penetrate the inner glass tube and thus continuously carry away negative charges, whereas the positively charged α-rays are retained by the tube, it follows that the latter will become more and more positively charged. In consequence of this the electroscope leaves become more and more deflected until they touch the glass walls of the outer vessel, when they are discharged and collapse, and the whole process is then repeated time and time again with the regularity of a 'clock'. The charge collected on the inner glass tube in such an arrangement may suffice to raise it to a potential of several hundred thousand volts.

The phenomenon of the 'ionic wind' is of great theoretical interest. The α-rays show this effect best, but β- and γ-rays are also effective. When the air between the plates of an ionization chamber is ionized, then on applying an electric field the air between the plates is set in motion. The direction of this current of air is from regions of stronger to regions of weaker ionization. It is caused by the fact that the moving ions exert a viscous drag on the surrounding molecules of air. Even when the distribution of ionization in the chamber is uniform, an ionic wind can still be detected, because the dragging action of the positive ions is somewhat greater than that due to the negative ions.

9. Atomic Disruption

The phenomenon of atomic disruption is the most potent action caused by the rays from radio-elements, and has as its basis the fact that we are enabled in this way to bombard individual atoms by means of rays which have a very high localized energy content. Atomic disruption has recently also been achieved by the aid of highly energetic protons and deuterons, and by neutrons even of small energy, and the results of such work, as well as those obtained with the rays from radium dealt with elsewhere in this book (see Chapter X, p. 108). It will su here if we again draw attention to this theoretically most impor application of the sources of energy rendered available by the rays radium, owing to its significant bearing on our ideas of the structu atoms.

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XXV

THE SIGNIFICANCE OF RADIOACTIVITY IN GEOLOGY AND IN COSMICAL CHEMISTRY AND PHYSICS

1. Determination of the Age of Minerals

The velocities of radioactive decay are natural constants characteristic of the disintegration processes under consideration, and are independent of all external conditions. They can be utilized for the measurement of time, for since they supply us with the functional relation between the amount of the substance transformed and the time, it is clear that the velocity of decay enables us to calculate the latter quantity when the former is known. Thus we could readily recognize the lapse of an hour without the aid of a clock if we noted the time taken for the activity of a preparation of ThC to fall to 49 per cent. of its initial value, as measured by a method, say, of steady deflexion. Such methods for the measurement of time have actually attained great importance in geology, the most significant of them being the following:

(a) Determination of the uranium-lead content of uranium minerals.
(b) Determination of the helium content of minerals and rocks.
(c) Measurement of the intensity of coloration of pleochroic haloes.

In all three cases we can readily calculate the time necessary for the attainment of the values found.

(a) *Age Determination from the Uranium-lead Content*

We have already seen (cf. Table 34, p. 143) that uranium, during its successive disintegrations, suffers the loss of eight α-particles before it reaches the stable end-product RaG, which is a type of lead. The following expression represents this transition:

$$\underset{238}{\text{U}} \longrightarrow \underset{32}{8\text{He}} + \underset{206}{\text{RaG}}.^{\dagger}$$

From this, and from the disintegration constant of uranium ($\lambda = 1{\cdot}57 \times 10^{-10}$ year^{-1}) it follows that 1 gm. of uranium produces in one year an amount of RaG equal to $1{\cdot}57 \times 10^{-10} \times \dfrac{206}{238{\cdot}07} = 1{\cdot}36 \times 10^{-10}$ gm. Thus if a mineral contains $1{\cdot}36 \times 10^{-2}$ gm. RaG to every 1 gm. of uranium, it follows that the age of the mineral is 100 million years. In general,

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[†] In the considerations of this chapter we shall disregard the influence of actino-uranium (^{235}U) on the results. This is permissible, seeing that ^{235}U constitutes less than 1 per cent. by weight of the element uranium (see p. 221), and hence, in spite of its more rapid rate of decay, the effect of disregarding it does not exceed the limits of error of the age determinations.

the age of a mineral in years is found by this method by dividin
amount of RaG corresponding to 1 gm. uranium by $1{\cdot}36\times10^{-1}$
by multiplying it by $7{\cdot}4\times10^{9} = 7{,}400$ millions. In this way we ob
the following useful formula for an approximate estimate of the ag

$$\text{Age} = \frac{\text{RaG}}{\text{U}} \times 7{,}400 \text{ million years;}$$

where RaG is the uranium-lead content, and U the uranium conte
the mineral concerned. In this calculation no account has been t
of the fact that in the course of long periods of time the quanti
uranium will have appreciably diminished as a result of disintegra
and that a somewhat lesser time will have been sufficient to pro
the amount of RaG found, from the previously greater quanti
uranium. To a first approximation we do justice to this correcti
utilizing the following formula for the determination of the age o
mineral:

$$\text{Age} = \frac{\text{RaG}}{\text{U}+0{\cdot}58\text{RaG}} \times 7{,}400 \text{ million years.}$$

Thus for the uranium pitchblende from Morogoro (Tanganyika T
tory) the ratio RaG:U = 0·093 was obtained, whence it follows th
age of this mineral is about 600 million years. In a similar way, th
of Norwegian bröggerite, for which the ratio RaG:U = 0·127,
out to be 870 million years.

Whereas the Morogoro ore contains no ordinary lead, most ura
ores have become more or less contaminated by ordinary lead i
process of geological changes. In making use of the analysis o
mineral, we must be able to differentiate between this disturbin
content and that of RaG, and this necessitates the performanc
determination of the combining weight of the mixture of lead is
(RaG+Pb) concerned, from which the Pb and RaG contents o
mineral can immediately be calculated. Thus the mixture of lea
topes extracted from uraninite from North Carolina is found to
a combining weight of 206·4, from which it follows that 70 per ce
the atoms of this mixed element are composed of RaG.†

The stable end-product of thorium (ThD) is also an isotope of lea
if the mineral contains thorium, the thorium and thorium-lead co
must also be taken into consideration in the determination of th
The simpler formula given above for the calculation of the ag
assumes the following form:

$$\text{Age} = \frac{\text{RaG}+\text{ThD}}{\text{U}+0{\cdot}33\text{Th}} \times 7{,}400 \text{ million years.}$$

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† $206{\cdot}4 = 0{\cdot}7\times206+0{\cdot}3\times207{\cdot}21$, where 206 is the atomic weight of RaG, an
the combining weight of ordinary lead.

But the number of uranium minerals practically free from thorium is so considerable that the thorium content can often be disregarded, the more so because, owing to its greater half-value period, thorium is not so effective as uranium in the production of lead (factor = 0·33).

From amongst the minerals whose ages have been determined by the method described, a uraninite from the Upper Cretaceous has been found to be one of the youngest (60 million years). This number thus gives us the age of the Upper Cretaceous System, if we make what appears to be quite a plausible assumption, that the uraninite concerned is a primary mineral, and has not gained access into the formation in the course of a subsequent epoch, in which case it would be secondary. The highest reliable values that have been obtained hitherto by the lead method amount to 1,100–1,400 million years; they were established for uraninites from the Middle and Lower Pre-Cambrian.

On the assumption (cf. p. 235) that the lead isotope ThD, the end-product of the thorium series, is completely stable, we should of course be able to determine the age of thorium minerals from their lead content in a manner exactly analogous to that used for uranium minerals. Here we must eventually apply the corresponding simple correction for the amounts of admixed uranium and uranium-lead (RaG). It has been found, however, that the ages of many thorium minerals calculated in this manner are so small (in some cases scarcely 10 million years), that here sources of error of one kind or another must be involved. In most cases weathering of the metamict thorium mineral and leaching out of part of the lead are the probable causes of the too small value of the lead-thorium ratio. All in all, the correct application of the methods described to the determination of the age of geological formations always entails the careful selection of well-preserved minerals, together with proof that they are of primary origin.

A still more important limitation of the 'lead method' is based on the fact that it is only applicable to radioactive minerals in the narrower sense, which contain uranium or thorium as an essential constituent, but not to ordinary minerals and rocks. In these last the quantity of uranium amounts only to from 10^{-8} to 10^{-5} gm./gm., and of thorium from 10^{-7} to 10^{-5} gm./gm. Since, in accordance with the age of the rock, the quantity of uranium-lead and thorium-lead formed from them is still smaller by one or two powers of ten, whereas the amount of ordinary lead admixed in rocks is of the order of magnitude of 10^{-5} gm./gm., it is clearly impossible to establish by atomic-weight determinations how much uranium-lead or thorium-lead is present. (Cf., on the other hand, the 'helium method', p. 267.)

In some minerals the ratio of lead to uranium has been altered by leaching-out processes in the course of the long periods of time involved, and this constitutes one of the uncertain factors in conne with the lead method. For this reason there is, in principle, some j fication for preferring a variant of the lead method, in whic determination of the age of the mineral is based on its relative co of actinium lead (AcD) and of uranium lead (RaG). Since a uranium (^{235}U) disintegrates about six times as quickly as urani the ratio of the amounts of AcD and RaG formed depends o time t during which the radioactive decay of the mineral has taking place, in accordance with the formula:

$$\frac{\text{AcD}}{\text{RaG}} = \frac{\text{Activity due to AcU}}{\text{Activity due to U}_{\text{I}}} \times \frac{\lambda_{(\text{U}_\text{I})}}{\lambda_{(\text{AcU})}} \times \frac{(e^{\lambda_{(\text{AcU})}\cdot t}-1)}{(e^{\lambda_{(\text{U}_\text{I})}\cdot t}-1)}.$$

Since AcD and RaG are isotopes, we can be certain that their cannot have been altered by leaching-out processes and the lik this ratio can be determined by densitometer measurements hyperfine structure of the spectral line 3,572 A.U. [1].

Experiments so far carried out have shown that this method determination is practicable. Unfortunately several grams of le necessary for this purpose, and its application is therefore limi radioactive minerals. The method cannot be used for the determi of the age of rocks.

(*b*) *Age Determination from the Helium Content*

As mentioned above, the uranium atom undergoes eight formations before it is converted into RaG. The majority o α-particles are brought to rest within the mineral, and are reta it as gaseous helium, which does not escape until the powdered sample is dissolved, fused, or heated, when it can be collect measured. From the disintegration constant of uranium it calculated that 1 gm. of uranium in equilibrium with its suc products produces annually $1{\cdot}18 \times 10^{-7}$ c.c. helium. The requi in years of a uranium mineral is thus found by dividing the q of helium (measured in c.c.) produced by 1 gm. of uranium in the by $1{\cdot}18\times10^{-7}$, or by multiplying it by $8{\cdot}5\times10^{6}$; in this way we the formula

$$\text{Age} = \frac{\text{He}}{\text{U}} \times 8{\cdot}5 \text{ million years.}$$

In the analysis of feebly active rocks, with which we are concerned here, it is usual to calculate the uranium content f radium content on the basis of the relation that about 3×10^{6} uranium correspond in radioactive equilibrium to 1 gm. of radi

206). For this reason it is advisable to insert the radium content directly in the above formula, which then assumes the form:

$$\text{Age} = 2{\cdot}8\frac{\text{He}}{\text{Ra}}\ \text{years.}$$

In these expressions the disintegration of the uranium has not yet been taken into account, as a result of which the values of the age come out somewhat too large (cf. what has been said above in connexion with the lead method). For the exact calculation of the age of 'old' rocks the following formula allows for the disintegration of the uranium:

$$\text{Age} = 1{\cdot}47\times 10^{10}\log\left(1+4{\cdot}42\times 10^{-10}\frac{\text{He}}{\text{Ra}}\right)\ \text{years.}$$

When thorium as well as uranium is present in the mineral, it is of course necessary to make allowance for its contribution to the production of helium. Since the helium method has recently been used frequently for rocks, and these always contain thorium as well as uranium, it will be convenient to give also a formula for calculating ages up to several 10^8 years, when the helium is derived both from thorium and uranium:

$$\text{ge} = \frac{\text{He}}{0{\cdot}35\ \text{Ra}+3{\cdot}0\times 10^{-8}\ \text{Th}}\ \text{years.}$$

When the 'helium method' was first applied to minerals, it gave values for the age which were mostly only about one-half or one-third of the values found by the 'lead method'. The reason for this was certainly to be sought in the fact that helium readily escapes from many minerals, so that only part of the helium produced by uranium and thorium during geological epochs is available for analysis. The probability of escape of helium is greater the greater the amount of helium that has accumulated in the mineral, or the greater the activity of the mineral. Thus in thorianite, which contains up to 9 c.c. helium per gram, the pressure at 0° C. can reach values even higher than 250 atmospheres; the likelihood of a loss of helium from such a mineral is so great that we can hardly expect to obtain correct values for the age from it.

Fortunately, however, the gas-analytical method of detecting helium is so sensitive that the amounts present even in rocks can readily be determined quantitatively, and at the same time we can be certain that the whole of the helium has been freshly formed by radioactive processes since the solidification of the rock. This is in marked contrast to the case of the 'lead method', where only a part of the element lead found in rocks is freshly formed RaG or ThD, the major portion of the lead having been taken up into the mineral during its formation (see above, p. 265). Nevertheless, it has been found that even rocks that contain only about 10^{-5} c.c. helium per gram suffer an appreci loss of helium even when they are reduced to powder, and when t are left for long periods in contact with the air they may lose u 60 per cent. of their helium content. The losses are still greater i at any time during its geological history the rock has been heated; helium content can be driven off in this way until less than 1 per c remains, more especially when we are dealing with a coarse-grained r

It has been found, however, that fine-grained rocks have c retained the whole of the amount of helium to be expected from t geological age and their contents in uranium and thorium. By ca choice of rocks and by careful treatment of them it is therefore pos to obtain reliable values for the age by means of the 'helium meth The evidence for this is not based solely on the fact that the valu found are in accord with determinations that have been carried o radioactive inclusions by the 'lead method' and with other geolo criteria. The most convincing evidence is supplied by the fact rocks taken from the same geological deposit give age determina in very good agreement, even when their uranium and thorium con vary. The following example of this has been taken from an inve tion on the age of Keweenawan trap rocks:

$He \times 10^5$ (*c.c./gm.*)	$Ra \times 10^{13}$ (*gm./gm.*)	$Th \times 10^6$ (*gm./gm.*)	Th:U	Age (10^6 yea
5·36	1·15	1·73	5·12	555
2·30	0·58	0·63	3·68	565

Results in like good agreement have been gained from other o rences, so that the applicability of the 'helium method' for the d mination of the geological age of rocks may be taken as proven. opens up to this method a much greater range of material th available to the 'lead method', which is limited to radioactive min and there is good prospect that by this means it will be possil construct a complete geological time scale, even on points of det

In applications of the 'helium method' to rocks it is none th necessary for us to have information on the source of the spec and on their treatment before the commencement of the che analysis. But this restriction is invalid when the method is appl metals, for these are so impervious to helium that even on heati helium can escape from them, so that the manner of collectin storing it is in this case of no moment. Terrestrial metals cont a sufficient admixture of uranium or thorium do not appear to frequent occurrence. On the other hand, it has been possible to the method to iron meteorites, which contain measurable amou uranium and helium, but their thorium content is so small that not yet been possible to take account of it in the analyses, and the values found for the age are therefore maximum values, which may be about 30 per cent. too high. They vary between the limits 100 and 2,800 million years, and in no case that has so far come to our notice does the age exceed that which is assumed for the planets, on the basis of various astronomical evidence. This result lends support to the assumption that the meteorites belong to the solar system, which is probable also for other reasons.

Age Determination from the Intensity of Coloration of Pleochroic Haloes

The α-rays produce coloration in glass, quartz, mica, and in similar materials (see p. 248), the depth of coloration depending on the number of α-particles that traverse the material. A strong preparation of radium produces an appreciable coloration in the course of only a few hours, but the same effect could be produced if a preparation of one-millionth the strength were allowed to act for a period a million times longer. It follows that we can construct an empirical scale of colorations, produced, say in mica, by different amounts of radium in the course of a day's exposure. By means of this scale we can find a rough estimate of the time that would be necessary for an active substance of known strength to act on the mica in order to produce a given depth of coloration.

Such colorations actually occur in natural minerals. Thus we are familiar with varieties of the following minerals that have been coloured by means of α-rays: rock-salt, fluorspar, spinel, garnet, tourmaline, mica, and hornblende. α-particles are emitted radially from the small radioactive inclusions in such minerals, and produce coloration within a sphere of radius equal to the range of the particles. In thin sections these colorations appear as circular patches, and when examined in polarized light they show the property of 'pleochroism'—whence the name 'pleochroic haloes'. The radius of these spherical colorations amounts to only 0·0034 cm., corresponding to the range in mica of the longest α-particles here involved, those of RaC′.

The exceedingly long interval of time during which these minerals containing inclusions have been subjected to radioactive radiations makes it possible in such cases to detect the effect of an amount of radium as small as 10^{-19} gm. This amount is a million times smaller than the amount determinable by electrical means (cf. p. 225). In age determinations we must, of course, also know the amount of radioactive material contained in the inclusion, in addition to the depth of coloration. This cannot be determined directly, but from a knowledge of the mineral of which the inclusion is composed, and by measuring its size with a microscope, an estimate of the quantity of radioactive matter in the inclusion can be formed, but only very approximately. Moreover,

since the intensity of coloration may have been changed during
logical time by thermal and similar processes, and a reversal may
occurred by over-exposure to the effect of the rays, just like the wea
ing (reversal) of the image which occurs with a photographic plate.
method of determining the age of minerals cannot lay great clai
reliability.

When attention is paid to details of the coloration, the phenom
of pleochroic haloes can be made the basis of a better metho
determining the age of minerals. The uranium mineral, which a
inclusion forms the centre of a halo, contains all the α-rayers o
uranium and actinium disintegration series in radioactive equilib
The various α-rays have different ranges, and the intensity o
resulting coloration appears to be greatest towards the end of the r
(Cf. the ionizing action of the rays, Fig. 11, p. 28. However,
more is known about the nature of the coloration process than
it consists of a kind of photochemical reaction, and accordingl
coloration also varies with the chemical composition of the parti
variety of mica—cf. p. 248.) An especially striking similarity t
action of light on a photographic plate consists in the fact that cl
intense regions of blackening there are developed zones of particular
ness ('Eberhard effect', cf. p. 248). All this has the result that the r
of the various α-rayers manifest themselves in the microscopic im
a pleochroic halo in biotite mica as separate rings (see Fig. 52, Pla
[2]. By special technical means (halo photometer) it is possi
record photometrically the intensity of blackening along the dia
of a halo. Fig. 53 shows the curve of blackening corresponding
halo in Fig. 52, and Fig. 54 gives a composite tracing of the r
for two normal haloes (uranium). In this last figure the kinks
curve are designated by letters, and the rings in the halo which
detected optically are indicated below the figure. The distan
these kinks from the centre of the halo can be accurately mea
and by taking account of the chemical composition of the materi
ranges in air can be calculated from them (range in mica = *c.* 5
of the range in air). For the kinks in the curve designated
letters *A* to *J* the average values (Table 50) of the ranges were fo

From this table we see that the point *A* agrees with the end
range of the α-particles from RaC′; *D* with RaA; *F* with the
equal ranges of radon and polonium; *H* with Ra, Io, and U_{II};
with U_I. It is thus possible to account for all the α-rayers
uranium-radium series.

The maxima of the curve of blackening (*B*, *E*, *G*, and *J*) have
ally no simple relation with the ranges, but the minimum *C* r
to be explained. This appears to correspond to the end of the

the α-particles from actinon and AcC. Since the parent substance the actinium series, actino-uranium, has a shorter half-value period han uranium I, it is to be expected that the ring corresponding to Ac–AcC) will be found to stand out more strongly relative to the

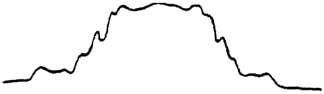

Fig. 53. Photometer Record of a Normal Halo in Biotite (Murray Bay, Quebec).

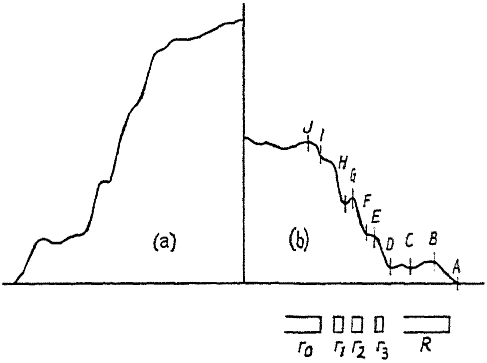

Fig. 54. Composite Photometer Record of Normal Haloes in Biotite from (a) Mt. Apatite, Maine; (b) Murray Bay, Quebec.

Table 50

Dimensions of the Halo Rings (Uranium Haloes)

	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
Radii in microns	34·4	30·5	27·1	23·1	20·6	19·7	16·9	15·6	12·4	9·5
Air equivalent in cm.	6·97	6·19	5·50	4·69	4·18	4·00	3·43	3·16	2·52	1·93

others, the greater the age of the halo. This has been found to be the case, and the photometric measurement of pleochroic haloes can be used, on the strength of this fact, as the basis of a method for the determination of geological time.

Up to the present even this improved method has not yielded such accurate results as the lead or the helium methods, and it is also far from being so generally applicable as the latter methods. But the investigations on pleochroic haloes merit attention for other reasons also. The agreement of the ranges found in them with those which now be observed affords proof of the fact that even millions of y ago the ranges of the α-raying radioactive substances, and hence their rates of decay (cf. p. 105), were no different from what they to-day. A ring of radius 42·6 μ, corresponding to the range of T (8·62 cm.), is occasionally found along with the rings that are due to uranium-radium series and the actinium series. Hitherto, longer ra have never been observed in the haloes, but shorter ones of r 8·6 μ and 5·2 μ and of uncertain origin have been found. The c sponding ranges in air would be 1·74 and 1·05 cm. Whereas the la may be due to samarium (R = 1·15 cm., see p. 235), the range of 1·74 is perhaps to be attributed to an α-rayer as yet unknown, and a fur study of pleochroic haloes may prove fruitful in its discovery.

Analogous results to those obtained with the uranium family also been obtained by observations with the halo photometer of chroic haloes due to the thorium family in biotite mica. The rad the five rings observed in thorium haloes satisfactorily account fo the α-particle ranges of the thorium series. The results are show Table 51 (cf. Table 1, p. 22). The last result in the table probabl

TABLE 51

Dimensions of the Halo Rings (Thorium Haloes)

Radii in microns	41·80	33·5	27·77	23·86	20·00	15·2	12·38	
Air equivalent in cm.	8·55	6·85	5·68	4·88	4·09	3·10	2·53	
Origin	ThC′	RaC′	ThA	Tn ThC	ThX RdTh	U_{II} Io Ra	Th	S

the same origin as the range 1·05 cm. found in the examinati uranium haloes. On this assumption, the mean radius of 40 such was found to be 1·18 cm., with a probable error of 1 per cent. The of the range found for thorium is of particular interest, as recent v obtained directly in a Wilson cloud chamber differ appreciably and 2·87 cm.) [3].

2. The Distribution of Radioactive Substances

It has already been pointed out in Chapter XXII, on the extra of radioactive substances, that uranium and thorium minerals ser sources for all the radio-elements of long life. In particular, the e tion of radium from pitchblende and from carnotite was then desc It will serve a useful purpose if we now give a summary (Tabl of the most important uranium and thorium minerals that may be for the extraction of radium, mesothorium, and their disinteg products.

TABLE 52

Summary of the Most Important Radioactive Minerals

I. URANIUM MINERALS

Name of mineral	*Chemical constitution*	*Content of* U_3O_8	*Most important mineralogical properties*
Pitchblende, uraninite	Uranium oxide. (UO_2 with UO_3)	60–90%	Black, rounded glassy masses, rarely crystals, greenish-grey streak.
Carnotite	Potassium uranium vanadinate. $K_2O \cdot 2UO_3 \cdot V_2O_5 + 2H_2O$	55%	Greenish-yellow crusts and nodules.
Autunite, calcium uranium mica	Calcium uranium phosphate. $CaO \cdot 2UO_3 \cdot P_2O_5 + 8H_2O$	63%	Canary-green four-cornered plates.
Chalcolite, copper-uranium mica	Copper uranium phosphate. $CuO \cdot 2UO_3 \cdot P_2O_5 + 8H_2O$	61%	Emerald-green four-cornered plates.
Uranium ochre	Various uranates and uranium sulphates	c. 17%	Intense yellow, earthy or in tangled threads.
Kasolite	Lead uranium silicate. $3(PbO \cdot UO_3 \cdot SiO_2) + 4H_2O$	48%	Yellow, earthy.
Pilbarite	Thorium lead uranate	27%, with 31% ThO_2	Yellow, knotty.

The other uranium minerals, like bröggerite, cleveite, etc., have so far been of no economic importance.

II. THORIUM MINERALS

Name of mineral	*Chemical constitution*	*Content of* ThO_2	*Most important mineralogical properties*
Monazite	Phosphates of the Cerium Earths + Th	Up to 18%, with 31·3% CeO_2	Monoclinic.
Thorite, orangite	$ThSiO_4 + H_2O$	Up to 81·5%	Tetragonal, isomorphic with zircon, $ZrSiO_4$.
Thorianite	$(ThU)O_2$	53%, with 47% UO_2	Regular, related to crystallized uranium pitchblende.

It will be noticed from the above tables that pilbarite and thorianite are minerals intermediate between those of uranium and those of thorium.

Noteworthy is the fact that even minerals like bröggerite and thorianite, although they are very old and strongly radioactive, have been able to retain completely or in large measure the original arrangement of their crystal lattice, as has been established by means of investigations with X-rays. Nevertheless, it can be calculated that about every eighth uranium atom must have disintegrated since the bröggerite w formed, and the crystal lattice must have been traversed by about many α-particles as there are uranium atoms contained in the latti

Small quantities of thorium, uranium, and of their disintegrati products can be detected in rocks, in fresh- and in sea-water, in t atmosphere, and in meteorites. To establish the presence of thori or of uranium it is customary to measure the constant amount of tho or of radon present in the material, since these can readily be recogniz

The mean uranium content of 1 gm. of rock in the earth's cr amounts to 4×10^{-6} gm., corresponding to $1{\cdot}3\times10^{-12}$ gm. of radi the thorium content being $1{\cdot}6\times10^{-5}$ gm., but these values vary v much with the nature of the rock. Acid rocks are much more stron active than basic rocks. Further information on this subject is gi in Table 53, which contains the uranium and thorium values for vari granites, basalts, and deep-seated rocks, and in which the potassi contents of the rocks are also entered, as well as the amount of h generated per annum by all these radioactive constituents. We s return to the geological significance of this production of heat in next section.

TABLE 53

Radioactive Content and Heat Production of Different Rocks

	1 *gm. of rock*			
	contains			
Type of rock	*Uranium* (10^{-6} *gm.*)	*Thorium* (10^{-6} *gm.*)	*Potassium* (10^{-2} *gm.*)	*yields per ann* *heat* (10^{-6} *cal*
Granite . . .	9·0	20·0	3·4	12·1
Grano-diorite . .	7·7	18·0	2·5	10·5
Diorite . . .	4·0	6·0	1·7	4·8
Central basalts:				
Continental . .	3·5	9·1	1·9	5·1
Oceanic. . .	3·6	7·1	1·8	4·7
Plateau basalt . .	2·2	5·0	0·8	3·0
Gabbro . . .	2·4	5·1	0·7	3·2
Eclogite . . .	1·0	1·8	0·4	1·3
Peridotite. . .	1·5	3·3	0·8	2·0
Dunite . . .	1·4	3·4	0·03	1·9

According to their chemical composition, stone meteorites are more strongly basic than the ultrabasic terrestrial rocks; in good a ment with this is the fact that the average uranium content of 20 s meteorites has been found to be $3{\cdot}6\times10^{-7}$ gm. The uranium co of iron meteorites is still smaller; on the average it amounts to 9×10^{-8} gm., corresponding to 3×10^{-14} gm. radium. From the commonly occurring terrestrial metals only one specimen has accurately examined up to the present; copper from Michigan contained less than 6×10^{-9} gm. of uranium.

The radium content of sea-water is about a thousand times less than that of the earth's crust, and averages between 10^{-15} and 10^{-16} gm. per c.c. Samples taken from near the coast are in general more active than those from the high seas. In the Pacific Ocean and in the Polar Seas the radium content is smaller than 1×10^{-15} gm.: in the Atlantic Ocean the values fluctuate between $0{\cdot}3 \times 10^{-15}$ and 40×10^{-15} gm. per c.c. (this high value was observed near the Irish coast). In the Adriatic Sea the value 2×10^{-15} gm. per c.c. has been found.

The radium content of large rivers is of the same order of magnitude as that of sea-water. Much greater activities are found in a few 'radioactive' spas and thermal springs. Their greater radioactivity is usually due only to radon that has been taken up by the water in its passage through rocks of good emanating power, and containing radium; because of this, the activity is not constant. One of the most active waters is that from the Joachimstal mines, which contains 7×10^{-10} curies or 2,050 mache units per c.c. The emanation content of various springs is given in Table 49, p. 227. In the water of individual springs, however, the element radium has also been detected in strikingly high concentration. Thus spring-waters in the neighbourhood of the thermal springs at Gastein contain 10^{-13} gm. radium per c.c., or about 100 times as much as the water of the seas and rivers. A distinctly higher radium content has been found in the water of certain petroleum bore-holes; in Germany up to 5×10^{-12} gm. radium per c.c. has been found, and in the northern Caucasus there are mineral oil sols that contain up to 10^{-10} gm. radium per c.c. It is not impossible that there may be a connexion between this concentration of radium and the genesis of the petroleum oil-fields, say by the storing of barium or uranium by the organisms responsible for the formation of the petroleum. In like manner attempts have been made to explain the occurrence of sources of helium in the regions from which petroleum is obtained.

Since the soil always contains radium, emanation is constantly diffusing with the soil gases into the atmosphere, but as we ascend to higher levels above the ground the amount of the emanation and of its disintegration products steadily becomes less and less, in consequence of their decay. The concentration of emanation in the soil gases depends naturally not only on the radium content of the rocks concerned, but also on the prevailing physical conditions. In general, the gases granite formations are richest in emanation, and those of sandy ground poorest. Rain and frost keep the emanation at lower levels, whereas the effect of strong sunlight on the ground, of winds, and of diminishing atmospheric pressure is to facilitate its escape into the free atmosphere

The average emanation content of the ground gases amounts to $2\times 10^{-}$ curie per c.c., and that of the free atmosphere $1{\cdot}3\times 10^{-16}$ curie, or on one two-thousandth part of the amount. Accordingly, the atmosphe contains on the average about 1·6 atoms of emanation in 1 c.c. I taking into account the decay of the emanation, it can be calculat that 1 cm.^{2} of the earth's surface gives off roughly 4×10^{-17} curie emanation to the atmosphere per second.

The conditions are quite different out at sea. In mid-ocean t emanation content of the air amounts to only about 1 per cent. of t mean value over land, whereas near the coasts much higher values a found, especially with a land breeze. From this it follows that t emanation content of the air over the sea is derived mainly from t land. This is consistent with the fact that the disintegration produ of thoron and actinon can also be detected in the air over land surfac but not over the sea, since these two forms of emanation are too sho lived to be able to traverse long distances.

A small activity is also found in atmospheric precipitation. Rain a snow do not carry down with them the gaseous emanation, but th do pick up its solid disintegration products that are suspended in atmosphere, and in this way they derive their activity.

Attempts have frequently been made to detect spectroscopically occurrence of uranium, radium, and thorium in the stars, but evidence is not yet unequivocal. At the same time it is almost cert that these three elements are present at least on the sun, for since earth has been formed from the material of the sun, and we can assume the new production of the initial members of the radioact disintegration series on the earth, uranium and thorium must at t time have also been represented in the solar material. Moreover, si the process of radioactive disintegration takes place in the ou layer of the sun presumably exactly as on the earth, it is rende extremely probable that the whole of the later members of uranium and thorium series are also available in the material the sun.

3. Thermal Consequences of the Distribution of Radioact Substances

Since it was established that radioactive substances occur in terrestrial rocks, our views on the thermal development of the e have changed accordingly in a decisive manner. Before the disco of this source of heat it was regarded as certain that, after its separa from the sun, the earth was in the molten state, and that from this t onwards it had continuously cooled until it attained its present temp ture. On this view, however, science was led to a contradiction, to at according to physical calculations the time taken up by the cooling ess should not have amounted to more than about 20 million years, hereas it was necessary to assume a multiple of this period for the logical development of the earth. This conviction of geologists has eanwhile acquired a complete confirmation by the age determinations entioned in § 1 of this chapter. The very wide distribution of radioctive substances in terrestrial rocks led to the recognition of a new urce of energy, of which no account had been taken by physicists their earlier calculations. Since all radioactive substances produce eat (see p. 246), it is clear that the cooling of the earth must at least ave been retarded as a result of its content of the radio-elements.

The annual production of heat by uranium and thorium with their sintegration products, and also by potassium, are shown in Table 54.

TABLE 54

nnual Production of Heat by Uranium, Thorium, and Potassium

m. of uranium in equilibrium with its disintegration products gives $7{\cdot}9 \times 10^{-1}$ cal.;
m. of thorium in equilibrium with its disintegration products gives $2{\cdot}3 \times 10^{-1}$ cal.;
m. of potassium gives $1{\cdot}2 \times 10^{-5}$ cal.

It is seen from this summary that the production of heat per gram potassium is by four powers of ten smaller than that of uranium and orium, but from the geological point of view, owing to the more wideread distribution of potassium in rocks, its thermal contribution is ly by one power of ten less than those of uranium and thorium. Rubidium, on the other hand, can be neglected owing to its rarity. The evelopment of heat by various rocks containing uranium, thorium, nd potassium, calculated on the basis of the above numbers, has lready been given in Table 53, p. 274.

In order to be able to state with certainty anything about the total mount of heat developed by radioactive processes in the earth, it uld be necessary to know not only the uranium, thorium, and tassium contents of the rocks of the earth's crust, but those of the arth as a whole. On these points, however, there are as yet no reliable ata available. On the basis of chemico-geological considerations it is robable that uranium and thorium have been concentrated mainly in e lithosphere. If the assumption be made that the rocks are still dioactive only down to a depth of 16 km., and that the average tivity is equal to that of the surface rocks, the heat produced in this ay is already sufficient to balance completely the amount of terrestrial eat now given out into space. In other words, on the basis of this ntent of radioactive substances, the earth could have retained its ent temperature throughout geological epochs of unlimited duration.

As a matter of fact, it is extremely improbable that the deeper cru layers of the earth are entirely free from radioactive elements. view is supported by our physico-chemical knowledge on the distr tion of the elements between the various layers of melts, and als the analyses of meteorites mentioned above. The uranium conten iron meteorites (see p. 274) renders it almost certain that even in innermost core of the earth, which most likely consists chiefly of uranium is still present. We must therefore discuss the question what results follow when the earth's content of radioactive substa is so significant that their production of heat not only suffices to m tain the continuous flow of heat from the earth's interior to the su and beyond into space, but also brings about a heating of the int of the earth. Geologists have drawn attention to the fact that such an assumption would suffice to explain many hitherto puz facts of the earth's history, such as geological cycles, mountain fo tions, and perhaps also the displacement of the continents. The e of heat would result in a fusion of deep-seated layers and this w necessarily call forth powerful movements in the earth's interior. movements would then again create the possibility of cooling freezing of the layers concerned, until after millions of years i would again take place in a new cycle. Owing to the uncertainty the assumptions on the quantity and distribution of the radioa substances in the earth, these considerations are for the time strongly hypothetical, and for this reason we shall not discuss th greater detail.

4. Ionization of the Atmosphere. Cosmic Radiation

It has long been known that atmospheric air is always ionize certain degree, and to this is due its ability to discharge elect charged bodies (cf. p. 7). Owing to their tendency to recombin and also because of the electrical field of the earth, these atmos ions would necessarily vanish in a few minutes, if provision we continuously made for their formation afresh by one or anothe of ionizing agency.

The presence of radioactive substances in the earth and to some also in the atmosphere itself suggests the idea of regarding the tion of the air as a consequence of the rays emitted by these subs From the quantity of ions present on the average near to the gro the atmosphere, and from the velocity of their recombinatio necessary to conclude that 10 to 13 pairs of ions are freshly form second per c.c. The question now arises whether the quanti distribution of the radioactive substances suffice for the expla of this ionization.

In the study of this question a very curious phenomenon presented itself. Although the amount of the radio-elements in the atmosphere continuously diminishes with increasing distance from the ground (see p. 275 et seq.), and the effect of the gamma radiation emitted by the earth in the same direction must also diminish, it was found in balloon flights that the ionization produced in gamma-ray electroscopes increases again in the higher levels of the atmosphere. The explanation could only be that a penetrating radiation not of terrestrial origin is present, which, owing to the smaller absorption by the earth's atmosphere, will, of course, manifest itself more strongly at greater heights. Further investigations have shown that this radiation differs not only in its origin but also in its large amount of energy from all types of radiation known to be due to the atomic disintegration of radioactive substances.

The flux of energy of this ultra- or cosmic radiation striking the earth's surface per second is by no means insignificant, but amounts to $3{\cdot}5 \cdot 10^{-3}$ erg per sq. cm. It is thus equivalent to the stream of energy of several hundred α-particles per sq. cm. per second, and of about the same magnitude as the luminous and thermal energy that reaches the outer confines of the atmosphere from all the fixed stars.

With sensitive apparatus it has been possible to detect this abnormally penetrating radiation also at sea-level, where it effects the formation in the atmosphere of about 1·5 pairs of ions per c.c. per second (cf. p. 282). By the use of self-registering electrometers sent up into the atmosphere with sounding balloons, the variation of the ionizing effect of this penetrating radiation has been measured up to heights of about 25 km. At this height the pressure of the atmosphere is only 22 mm. of mercury, so that it is only necessary to take into account 3 per cent. of the atmosphere as the absorbing medium above the ionization chamber. At this level in the atmosphere the ionization rises to the value of $330\,I$.† Conversely, when self-registering electrometers were sunk in lakes, the ionizing effect of this radiation diminished continuously, and at a depth of 250 metres it amounted to less than $0{\cdot}01\,I$, or less than one-thirty-thousandth part of its value in the uppermost layers of the stratosphere. These experiments show that this radiation penetrates through the atmosphere from outside, and that it requires a layer of 250 m. of water to render its effect practically negligible, so that it possesses a much greater hardness than the hardest γ-rays known to us.

It has been possible to obtain more exact information on the direction of the rays by using two Geiger counters arranged some distance apart, instead of an ionization chamber, for the detection of the rays. When one of the counters is arranged vertically over the other counter, the

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† $1\,I = 1$ pair of ions per c.c. per second.

two counters give simultaneous registrations more frequently th
other relative positions of the counters. The simultaneous functi
of the two counters is obviously brought about by penetrating pa
that shoot through both counters, and the fact that this phenon
arises more frequently when the counters are arranged one verticall
the other proves that this kind of radiation approaches the earth
in a vertical direction. Insertion of sheets of lead between the co
only slightly diminishes the number of simultaneous discharges (
dences), and this proves that we are here confronted with an
ordinarily penetrating kind of radiation, and thus manifestl
cosmic rays. The fact that the rays preponderate in the vertical
tion is most simply explained on the assumption that the radiati
is incident on the earth's atmosphere is more strongly absorbe
other directions on account of the greater thickness of the atm
then traversed.

Although the major part of the radiation is constant at a giver
slight fluctuations have been detected, and these seem to be rel
the time of day and year, and to irregularities in the earth's mag
On the other hand, it has been found that it shows clearly a depe
on the geographical latitude of the place of observation. When d
places at sea-level are compared it is found that the intensity
radiation is smallest at the equator, that it rises in value no
south of the equator, and reaches a 14 per cent. higher val
latitude of 50°. This last value is maintained from there to th
At a height above sea-level of 4,000 m. the percentage inc
intensity with geographical latitude amounts to over 30 per ce
dependence on latitude renders it extremely probable that an e
part of the radiation consists of charged particles.

The best experimental tool in the study of the nature of
particles is the Wilson expansion chamber (see p. 19). The app
of this method to the penetrating radiation was rendered more
by the fact that, owing to the small absolute intensity of the r
at sea-level, cloud tracks which could be ascribed to the cosmic r
were to be found naturally on only a small fraction of the
photographs. But by combining the Wilson chamber with th
mentioned device of the dual Geiger counter, it was possible b
of a self-releasing mechanism to effect the working of the
chamber always only at the moment when a penetrating part
traversed both counters and the Wilson chamber. By this m
number of successful exposures was more numerous, and the
the plates obtained in this way was exceedingly fruitful. It w
that the penetrating radiation consists of approximately equal
ties of positive and of negative electrons (positrons and el

possessing exceedingly high energy values of 10^8 to 10^9 electron volts, and in individual cases as high as 10^{10} e.V.

This explains the results on the geographical distribution of the penetrating radiation. Theoretical considerations closely related to the explanation of why the aurora only occurs in the neighbourhood of the poles (cf. p. 283) lead us to expect that positive and negative electrons that are incident on the atmosphere from outside must possess an energy greater than 10,000 million electron volts in order that they may strike the earth at the equator. At a latitude of 30° even less than 7,000 million electron volts and at a latitude of 45° 4,000 million electron volts suffice for them to reach the earth. Round the poles north and south of latitudes 45° still smaller energies should suffice, if account had to be taken only of the magnetic field of the earth; but since a smaller energy is insufficient for the rays to penetrate the atmosphere no further increase in the intensity is to be expected beyond these latitudes, and as already mentioned no further increase has been observed. In order to understand why the rays are able to penetrate to a depth of 250 m. in water, we must assume that some of the electrons and positrons possess an energy of more than 100,000 million electron volts.

The nature of the true 'cosmic' radiation which enters the outer atmosphere from beyond need not necessarily be the same as that observed at sea-level. Thus it has been found that at a height of 2,500 m. the intensity of the radiation coming from the west is 15 per cent. higher than that of the radiation coming from the east; this seems to indicate that in this case most of the incident particles consist of positrons. Apart from the tracks of individual particles, however, the photographs obtained with a Wilson cloud chamber also show the sudden and simultaneous appearance of a large number of tracks, all of which originate near one point within the Wilson chamber. From their position and the direction of their magnetic deflexion, these tracks seem to be due to electrons and positrons. The interpretation of these 'showers' is probably that under the influence of the extraordinarily energetic cosmic radiation, when an atom is struck it is caused to disintegrate explosively and thus gives rise to new tracks, but the more detailed mechanism of the production of showers has not yet been elucidated. Other penetrating cosmic-ray particles have also been detected. Lighter than protons these 'heavy electrons' are probably produced in the upper atmosphere

Still less is known about the mode of origin of the cosmic rays than about their nature. Their practical uniformity by day and night shows that the sun is not the principal source responsible for the rays, and since no connexion with sidereal time is observable, the Milky Way i likewise excluded as the place of origin of the rays. Neither can the interior of the stars be held responsible, for the energy of the radiatio

would be reduced in its passage through the material of the stars.
the only sources that call for consideration in the production o
radiation seem to be the outer layers of the stars, nebulae, or the
stellar matter present in space. But at the present time we know
process of transformation of matter in which energies of 10,000 m
e.V. and more could be produced. Not even the hypothesis of the
annihilation of matter seems adequate for the purpose, for the co
disappearance of the mass of a proton supplies only 1,000 millio
and we can hardly conceive the possibility that heavier atomic
vanish and in so doing transfer the whole of their energy to a p
or to a negative electron. For this reason, recourse has even been
to the conception that the cosmic radiation was formed at a much
period in the development of the universe, when processes now unl
to us were still possible, and that the radiation then produce
circulated uninterruptedly since that time in the universe, which a
ing to some modern theories is a closed system. Owing to the excee
rarified distribution of matter in the universe, a ray that had tra
the entire universe would have experienced only about one-hun
part of the absorption that would be effected by the earth's atmo

The contribution of the cosmic radiation to the ionization
atmosphere in the neighbourhood of the earth's surface, as men
above, is relatively small; a rough calculation shows that the es
part of the ionization of the air is accounted for here by the radi
substances in the atmosphere (especially the α-rayers Rn, RaA
Tn, ThA, ThC). In addition, the β- and γ-radiation from the
active substances contained in the earth is of importance, as
seen from the following Table 55, in which *I* denotes the forma
a pair of ions per c.c. per second.

TABLE 55

Ionization in the Neighbourhood of the Earth's Surface

By the α-, β-, and γ-rays from radio-elements in the air	
By the β- and γ-rays from radio-elements in the earth	
By the cosmic radiation	
Total effect of all known ionizing agents	

In view of the uncertainty of the bases of the calculation, th
ment with the empirical value of 10–13 ions given early in this
is satisfactory, so that it is not necessary to regard any other s
ionization, such as ultra-violet light, as of essential importanc
production of atmospheric ionization. As already mentioned, t
practically no radioactive substances present over the ocea
accordingly it has been possible to calculate that the very sligh

tion of the air over the high seas is to be regarded as primarily due to the effect of cosmic radiation.

5. The Aurora

Recent investigations have shown that the phenomena of the northern lights can be explained as a consequence of the penetration of electrons emitted by the sun into the earth's atmosphere. The occurrence of the aurora in polar regions and the obvious impossibility of their production in low latitudes, as well as the details of their form have been made intelligible as an effect of the magnetic field of the earth on the path of the electrons (see above, p. 281). However, no details are as yet known on the mechanism of the emission of electrons from the sun. Gases of the earth's atmosphere are excited to luminescence by the electrons. The existence of nitrogen is revealed spectroscopically by the presence of the first positive group of nitrogen bands in the red, and the red and green lines ($\lambda = 6{,}300$ and 5,577 A.) characteristic of the aurora have been identified as oxygen lines. These results are of particular interest inasmuch as they prove that even at the greatest heights at which the northern lights have been observed in the atmosphere i.e. up to several hundred kilometres, nitrogen and even the heavier gas oxygen are still present.

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XXVI

THE HISTORICAL DEVELOPMENT OF THE SCIENCE OF RADIOACTIVITY

ON the 24th of February 1896 Henri Becquerel read a paper before Academy of Science in Paris in which he stated that compound uranium emit rays that are able to affect a photographic plate thr material opaque to light. This casual observation was the star point in the development of a new branch of knowledge, to wit. r activity.† After Becquerel's discovery, numerous substances tested for similar properties to those shown by uranium, and result the radioactivity of thorium was discovered by C. G. Sch and by Mme Curie (1898). In the same year the systematic inves tion of different uranium materials led Pierre Curie and his wife t discovery of two markedly strong active substances in pitchblende of which was separated along with bismuth and named 'poloni whereas the second, 'radium', was found to give similar reactio salts of barium. Further investigation revealed the fact that it is difficult to concentrate polonium (Marckwald), but that radium substance sufficiently long-lived to permit of its preparation in w able quantities, and at the same time sufficiently short-lived to in a high degree the typical properties of a radio-element. In ad to these radium showed several other favourable properties, such production of a gaseous succession product of not too short life. amongst the most important of the remaining radioactive subst first actinium (1899) was discovered by Debierne and by Giesel, radio-lead by K. A. Hofmann, and radiothorium (1905) and thorium (1907) by Hahn. In the year 1907 ionium was discove uranium minerals by Boltwood and almost simultaneously by and Marckwald, and in the same year N. R. Campbell succee establishing the radioactivity of potassium and rubidium. Th covery of an additional radio-element of long life, protoactiniu not made until the year 1918 by Hahn and Meitner on one hand Soddy and Cranston on the other. In 1932 Hevesy and Pahl foun samarium was a radioactive substance. The production of h radium was observed at an early stage, but first measured in th

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1903 by Curie and Laborde; an especially accurate determination of this important quantity resulted later from the investigations of Schweidler, St. Meyer and Hess, and Rutherford.

By the discovery of radioactive substances a new and powerful field of natural phenomena was opened up, but at first there was lacking a satisfactory linking up of the numerous inexplicable individual phenomena with each other, as well as with the phenomena met with in other physico-chemical studies. Light was first shed on these problems by the disintegration theory, formulated by Rutherford and Soddy in the year 1902. According to this theory the emission of radiation by radioactive substances is a phenomenon consequent upon atomic transformation, and the theory made it possible to deduce quantitative information on the process of transformation from the nature and intensity of the radiation. The idea of a development of inorganic matter had frequently been conjectured in the course of the history of chemistry, and by virtue of the disintegration theory and the unbounded evidence in its favour, it has established itself permanently in the fabric of our knowledge. The disintegration theory of Rutherford and Soddy has thereby achieved the distinction of becoming one of the most important theories in natural science.

The investigations that resulted from the formulation of this theory at first proceeded mainly in two directions. First it was necessary to examine the nature of the rays from radioactive substances, and then to reveal the sequence of the transformation processes and the properties of the radio-elements.

In 1899 Giesel, St. Meyer and Schweidler, and H. Becquerel had already established the fact that part of the radioactive rays could be deflected in a magnetic field. A few years later Rutherford and his co-workers succeeded in identifying the exact nature of the α-, β-, and γ-rays. Of particular importance for the recognition of the nature of the α-rays was the work of Ramsay and Soddy, and of Rutherford and Royds, who showed that the rays are charged atoms of helium. P. Curie had already observed that they have a definite range, and the study of their properties was mainly the work of W. H. Bragg, Geiger, Marsden, Kleeman, Mme Curie and her collaborators, Rausch von Traubenberg, and others. Elster and Geitel on one hand, and Crookes on the other, made the observation that α-rays are able to excite scintillations in zinc sulphide screens, and this proved to be of great practical importance. Regener was the first to make quantitative counts of scintillations, and in a similar way Rutherford and Geiger succeeded in determining the number of α-particles emitted per second by 1 gm. of radium, and also the charge of an α-particle. Schweidler was the first to direct attention to the statistical nature of radioactive disintegration.

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The more detailed elucidation of the properties of β-rays was ca out in the laboratories of Lenard, J. J. Thomson, Rutherford, H Meitner, v. Baeyer, Geiger, Bothe, Danysz, de Broglie, and Kova that of γ-rays by Rutherford and his collaborators, Ellis in partic by W. H. Bragg, A. H. Compton, Meitner, and as a result of inves tions in the Vienna Radium Institute (K. W. F. Kohlrausch, I Lawson, and others). The method of C. T. R. Wilson for rend visible the tracks of the rays by condensation of water vapour has of the greatest service in the study of all three types of rays.

The phenomenon of recoil, which was discovered by Hahn an Russ and Makower and later investigated particularly by Wertens made possible the isolation of several elements of short life. The tion between range and disintegration constant, discovered by G and Nuttall in 1911, has proved very important in revealing the ence and for determining the period of elements both of very shor of very long life.

The nuclear theory of the atom, which is of paramount impor in modern physics, was advanced in the same year by Rutherfor was based on observations by Geiger and Marsden on the scatteri α-rays in their passage through matter, and furnished a satisfa explanation of this phenomenon. But on the basis of the classical of theoretical physics it was not possible to interpret the propert the stability of such a structure. Not until two years later wa achieved by Bohr, who utilized Planck's quantum theory for thi pose. The atomic theory founded by Bohr made it possible for th time to give a simple and numerical interpretation of absorptio emission spectra, to which phase of progress the work of Somm and his school, Kramers, and others belongs, and also elucidate extensive field of the phenomena of collisions between electron atoms, which was initiated by the work of Franck and Hertz. further development of the theory of atomic structure was nat linked most intimately with the fundamental successes of qua mechanics; for this reason mention must be made primarily names of Born, L. de Broglie, Dirac, Heisenberg, Pauli, and Schröd

The development of the study of X-rays is also closely related modern theory of the atom. The famous discovery of v. Laue was soon followed by the work of W. H. and W. L. Bragg on the tion of X-rays by crystals, and by Moseley's investigation c characteristic X-ray lines of the chemical elements, by virtue of the fundamental importance of the atomic number was estab (1913). But radioactivity itself also owes a debt to the develo of X-ray spectroscopy. Thus the measurement of the wave-leng γ-rays, as carried out by Ellis and by Meitner, first became a prac supposition when the spectroscopy of X-rays had made it possible to localize the individual groups of electrons in the extra-nuclear part of the atom, and to calculate the work necessary to separate an electron from the atom. Only in the case of soft γ-rays had Rutherford and Andrade succeeded previously in carrying out a determination of the frequency by the crystal method.

Meanwhile, important advances had also been made in radiochemistry investigations by Marckwald, Keetmann, Boltwood, Auer v. Welsbach, McCoy, Strömholm and Svedberg, Fleck, and others led to a conception held notably by Soddy as early as 1910, namely, the existence of radioactive elements, later called 'isotopes', which, in spite of differences in their atomic weights and radioactive properties, at the same time show the same chemical, electrochemical, and spectroscopic properties. On the basis of this view, and with the aid of more complete knowledge of the sequence of disintegration in the transformation series of the radio-elements, the radioactive displacement laws were formulated by A. S. Russell, and almost simultaneously by Fajans and by Soddy (1913), the results of the last two authors being satisfactory in every detail. Amongst other things, these laws made it possible to settle the question of the end-products of the disintegration series, and the conclusions formed in the course of this work were completely confirmed by atomic-weight determinations carried out by Richards, Hönigschmid and others. It became more and more clear that these results are of the greatest importance not only in radiochemistry, but also in general chemistry. The conception of a chemical element had to be restricted to its chemical inseparability, and even in the case of the ordinary elements it became imperative to reckon with the possibility that they might consist of more than one type of atom.

A few years later Aston proved by means of his mass-spectrograph that the phenomenon of isotopy is actually a general property of the elements. This apparatus was constructed by Aston as a further development of the pioneer work of J. J. Thomson on positive ray analysis. At the same time Aston's investigations (1919) revealed the fact that, to a first approximation, the atomic weights of the elements are integral in nature, even when their combining weights often show marked deviations from whole-number values. This invalidated the most important argument that perforce had always been raised against Prout's hypothesis, and rendered it probable that all the chemical elements are genetically related. Science was confronted with a new problem, that of separating the elements which occur in nature into their constituent isotopes, and in several cases this problem has been more or less completely solved. Owing to its singular properties, the heavy isotope of hydrogen was prepared in the pure state soon after its discovery by Urey. For other elements, the best results hav attained by G. Hertz in Charlottenburg, by use of his diffusion m

The first successful experiments to effect a transmutation non-radioactive elements also fall into the post-war period. S was first achieved in the case of nitrogen in 1919, when Ruth and Chadwick demonstrated that by bombardment with α-pa hydrogen nuclei (protons) are liberated from the atoms of this el these protons being projected as corpuscular rays of large range. F investigations have established that a large number of light ele can be transformed artificially in this way. In addition to the mentioned discoverers of artificial disintegration, many other w have taken part in the subsequent development of the subject, inc Kirsch, Pettersson, and Stetter in Vienna, Harkins in Chicago, B Berlin, and Pose in Halle. These studies have led to important conc on the structure of atomic nuclei, the constitution of which had main a closed book at the time of the formulation of the theory atom due to Rutherford and Bohr. They have not only introdu to the proton as a nuclear constituent, but during the course of t few years also to two further constituents of matter, the neutron positron. The neutron was discovered in 1932 by Chadwick b barding beryllium with α-rays, as a sequel to observations of and of M. and Mme Curie-Joliot. The positron was discovered same year by Anderson, and it was observed with greater certa 1933 by Blackett and Occhialini, using a Wilson cloud chamb product of the interaction of cosmic rays on matter.

Although for many years the only available means of trans atomic nuclei were the α-rays from radioactive substances, C and Walton succeeded in 1932 in the transmutation of light el by bombarding them with a beam of fast protons that ha accelerated in a discharge tube. This was the first time that mutation of elements had been achieved without the interventi natural radioactive process. The methods of accelerating the were varied in many ways, and in the year 1932 an ingenious called a cyclotron (see p. 290) was developed by E. O. Lawr California. This was also the first method to show that deute mass 2 are more efficient projectiles than protons of mass 1.

The experiments on the transmutation of elements entered ticularly interesting phase when, in 1933, M. and Mme Cur found that the product of atomic transformation in certain radioactive. The development of this fundamental discov sulted in the establishment, within a year or two, of a new of science, that of artificial radioactivity. In this rapid and development the two most outstanding events were those as with the names of Fermi and of Lawrence. Fermi found that artificially radioactive substances can be produced from most elements in the periodic system by bombarding them with neutrons, whereas Lawrence, by making use of his cyclotron (p. 290), succeeded in preparing artificial radioactive preparations of very great strength. As a result of these advances it also became possible to extend the periodic system of the elements by preparing radioactive isotopes of elements with an atomic number higher than that of uranium. Such 'trans-uranium' elements were first prepared by Fermi, and later studied in detail and with great success by Hahn and Meitner.

Successes have to be recorded in various other fields in radioactivity. The chemical effect of the rays from radium was studied in greatest detail by Lind and his co-workers, but also by Duane and Wendt, Kailan, Przibram, Mund, and others. Since 1913 radioactive indicators have frequently been utilized by Hevesy and Paneth in chemical and physical investigations; as a result of the discovery of artificial radio-elements, the number of problems whose study can be simplified by the use of radioactive indicators has increased enormously, especially in the field of biology. The applications of radioactivity to geological problems have been primarily the work of Boltwood, Strutt (Lord Rayleigh), Mügge, Joly, Holmes, Urry, and Ellen Gleditsch; whilst in the domain of atmospheric electricity mention should be made of the work of Elster and Geitel, v. Schweidler, Mache, Eve, McLennan, C. T. R. Wilson, Gockel, and Hess. With the name of Hess is also associated the particularly interesting discovery of an extra-terrestrial radiation of exceeding penetrability, which he detected in balloon flights. In addition to Hess, Kolhörster, Millikan, Hoffmann, Regener, Steinke, A. H. Compton, Blackett, and Clay, in particular, have taken part in the further study of this 'cosmic radiation', and the results of their observations are no less important in astrophysics than in atomic research. In these investigations, as well as in many other recent radioactive measurements, the electronic counter due to Geiger has played a prominent part. The suitability of the photographic plate for the direct study of ray tracks has been established, notably by the Misses Blau and Wambacher (Vienna).

This short historical survey may have served to show that, in the span of only 42 years since Becquerel's discovery, the science of radioactivity has developed from a special field of physics into one of the most important and most richly correlated branches of the entire realm of natural science.

APPENDIX

THE CYCLOTRON. (*See Index, p. 297*)

SINCE the achievement of nuclear disruption and of artificial radi activity, it has been the aim of physicists to secure bombarding ions ever greater energy, in order to facilitate the production of the nucle processes involved. The straightforward method of doing this by t use of larger and larger accelerating potentials for the ions, however, fraught with progressively increasing experimental difficulties. Mo over, at these very high potentials of the order of a million volts, it no easy task to produce concentrated beams of the ions in quantit adequate for many of the problems involved. These difficulties ha been evaded in the magnetic resonance accelerator or *cyclotron* by t development of the multiple acceleration of ions to high speeds with the use of abnormally high voltages.

In this method, which was initiated and developed largely by work of E. O. Lawrence and M. S. Livingston, semicircular hollow pla or dees, resembling the duants or binants of an electrometer, are moun in a vacuum with their diametral edges adjacent, and are situate a uniform magnetic field normal to the plates. High frequency osci tions are applied to the plate electrodes, and produce an oscillat electric field over the uniform diametral gap between them. I formed in the middle of the diametral region by accelerated electr from a heated spiral filament, are accelerated during one half-cycl the oscillating electric field into the interior of one of the electro where they are bent into circular paths by the magnetic field and l emerge again into the gap between the electrodes. By adjustmen the magnetic field so that the time required for the ions to trav a semicircular path within one of the electrodes is equal to a half-pe of the oscillations, the electric field will have reversed its direc when the ions return to the region between the electrodes, so that t receive a second increment of velocity on passing to the other electr The time required for the ions to traverse a semicircular path is i pendent both of the radius of the path and of the velocity of the i and hence, when the magnetic field has been correctly adjusted, the spiral round in resonance with the oscillating field until they reach periphery of the apparatus. Their final kinetic energies are as m times greater than that corresponding to the voltage applied to electrodes as the number of times they have crossed from one elect to the other. Both the magnetic and electric fields exercise a foc action on the ions and prevent any serious loss of ions as they accelerated, so that relatively good yields of high speed ion curr are obtainable in this indirect manner, and the focusing action results in the generation of beams of ions *c.* 1 to 3 mm. in diameter, which are ideal for experimental studies of collision processes. By means of a suitably arranged electric field the high speed ions can be deflected from the accelerating system and withdrawn completely from the apparatus into the air through a thin platinum window in the chamber wall.

In one of the earlier forms of the apparatus the pole faces of the magnet were 11 inches in diameter, and a current of 10^{-9} ampere of $1{\cdot}22 \times 10^6$ e.V. protons was produced in a tube to which the maximum applied voltage was only 4,000 volts. The high frequency voltage used in a more recent form of the apparatus is estimated to be from 50,000 to 100,000 volts, and with magnet pole faces $27\frac{1}{2}$ inches in diameter the ions are withdrawn from the accelerating electrodes at a distance of *c.* 12 inches from the centre of the system. With this apparatus pencils of many micro-amperes of deuterons having energies up to $6{\cdot}3 \times 10^6$ e.V. and of a few tenths of a micro-ampere of 11×10^6 e.V. doubly charged helium ions have been obtained. With such amounts of high speed deuterons incident on a beryllium target, the usual neutron emission with this apparatus is equivalent to the γ-radiation from about 100 gm. of radium, and for the protection of the operator (see pp. 258 and 260) the cyclotron is controlled at a distance of 40 feet from the target with suitable intervening absorbing material. Bombardment of sodium metal for one day with 20 micro-amperes of 5×10^6 e.V. deuterons produces radio-sodium having a γ-ray activity equivalent to that of 200 mg. of radium. In some of the recent forms of the apparatus the strength of the magnetic field is of the order of 18,000 oersteds, and the corresponding wave-length of the oscillating electric field used for accelerating deuterons or doubly charged helium ions is about 22 metres.

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TABLE 56

Artificially produced Radioactive Isotopes of the Elements†

Element and atomic number	*Radioactive isotopes*		
	Mass-numbers	*Half-value periods*†	*Particles emit*
2 He	6	1 s.	(−)
3 Li	8	0·8 s.	(−)
4 Be	10	> 10 y.	(−)
5 B	12	0·02 s.	(−)
6 C	11	20 m.	(+)
7 N	13; 16	10·5 m.; 9 s.	(+); (−
8 O	15; 19	2·1 m.; 31 s.	(+); (−
9 F	17; 18; 20	1·2 m.; 108 m.; 8 s.	(+); (+); (
10 Ne	23	33 s.	(−)
11 Na	22; 24	3 y.; 15 h.	(+); (−)
12 Mg	27	12 m.	(−)
13 Al	26; 28; 29	7 s.; 2·3 m.; 11 m.	(+); (−);
14 Si	27; 31	6·6 m.; 2·5 h.	(+); (−)
15 P	30; 32	3 m.; 14·5 d.	(+); (−)
16 S	31; 35	26 m.; 80 d.	(+); (−)
17 Cl	34; 38	33 m.; 38 m.	(+); (−)
18 A	41	110 m.	(−)
19 K	38; 42	7·5 m.; 12·5 h.	(+); (−)
20 Ca	39; 45	4·5 m.; 2·3 h.	(+); (−)
21 Sc	41; 42; 43; 44; 46 48	53 m.; 4·1 h.; 4·0 h.; 52 h.; 90 d.; 41 h.	(+); (+); (+); ((−)
22 Ti	51	3 m.	(−)
23 V	48; 49; 50; 52	16 d.; 32 m.; 3·6 h.; 3·8 m.	(+); (+); (+
24 Cr			
25 Mn	?; 56; ?; ?; ?	46 m.; 2·5 h.; 21 m.; 5 d.; sev. mths.	(+); (−); (−); (
26 Fe	55; 59	8·9 m.; 40 d.	(+); (−
27 Co	55; ?; 58; 60	18 h.; 150 d.; 11 m.; c. 1 y.	(+); (+ and − (−)
28 Ni	63	160 m.	(−)
29 Cu	61; 62; 64; 66	3·3 h.; 10·5 m.; 12·5 h.; 5 m.	(+); (+); (+ a (−)
30 Zn	63; 65	38 m.; 60 m.	(+); (−
31 Ga	66; 68; 70; 72	9·4 h.; 60 m.; 20 m.; 23 h.	(+); (+); (−
32 Ge	75; ?	20 h.; 30 m.	(−); (−
33 As	76; 78	26 h.; 65 m.	(−); (−
34 Se	79 or 81; 83	1 h.; 17 m.	(−); (−
35 Br	78; 80; 80; 82; 83	6·3 m.; 18 m.; 4·5 h.; 34 h.; 2·5 h.	(+); (−); (−);
36 Kr	?	74 m.; 4·5 h.; 18 h.	(−); (−);
37 Rb	86; 88	18 m.; 18 d.	(−); (−
38 Sr	89	3 h.; 55 d.	(−); (−
39 Y	90	70 h.	(−)
40 Zr	97	44 h.	(−)
41 Nb			
42 Mo	?	2·5 m.; 17 m.; 36 h.	

TABLE 56 (*continued*)

Element and atomic number	Radioactive isotopes		
	Mass-numbers	*Half-value periods*†	*Particles emitted*†
43 —	?	few months	
44 Ru	?	40 s.; 100 s.; 11 h.; 170 h.	(−); (−); (−); (−)
45 Rh	?	44 s.; 3·9 m.	
46 Pd	?	60 h.; 15 m.; 12 h.; 3 m.	
47 Ag	106; 106; 108; 110; 111; 112	24·5 m.; 8·2 d.; 2·3 m.; 22 s.; 7·5 d.; 3·2 h.	(−); (−); (−); (−) (−); (−)
48 Cd	?; 115; 117	33 m.; 4·3 h.; 58 h.	(−); (−); (−)
49 In	111; 112; 114; 114 116; 116; 117	20 m.; 72 s.; 4·1 h.; 50 d. 13 s.; 54 m.; 2·3 h.	(−); (−); (−); (−); (−); (−); (−)
50 Sn	?	8 m.; 18 m.	
51 Sb	120; 122; 124	16 m.; 2·5 d.; 60 d.	(−); (−); (−)
52 Te	?	1·1 h.	(−)
53 I	128	25 m.	(−)
54 X			
55 Cs	134	1·5 h.	(−)
56 Ba	?; 139	2·5 m.; 80 m.	(?); (?)
57 La	140	1·3 d.	(−)
58 Ce	139	2·1 m.	(+)
59 Pr	140; 142	3 m.; 19 h.	(+); (−)
60 Nd	147; 149; 151	84 h.; 2 h.; 21 m.	(−); (−); (−)
61 —			
62 Sm	151; 153	21 m.; 2 d.	(−); (−)
63 Eu	152; 154	27 h.; 9·5 h.	(−); (−)
64 Gd	159	3·5 m.; 17 h.	(−); (−)
65 Tb	160	3·9 h.	(−)
66 Dy	159; 165	2·2 m.; 2·5 h.	(−); (−)
67 Ho	164; 166	47 m.; 35 h.	(−); (−)
68 Er	165; 169; 171	5 h.; 7 m.; 12 m.	(−); (−); (−)
69 Tm	170	120 d.	
70 Yb	175; 175	2·1 h.; 41 h.	(−); (−)
71 Lu	176; 178	4 h.; 8 d.	(−); (−)
72 Hf	181	55 d.	
73 Ta	180; 182	8 h.; 97 d.	(−)
74 W	?	1 d.	
75 Re	?; 188; ?	20 m.; 18 h.; 85 h.	[illegible]
76 Os	?	40 h.	
77 Ir	192; 192 or 194; 189, 192, or 195	2 m.; 1·5 m. and 19 h.; 28 m. and 8·5 h.	[illegible]
78 Pt	197; 199	18 h. and 3·3 d.; 50 m.	(−)
79 Au	198; 199	2·7 d.; 13 h. and 4·5 d.	(−); (−)
80 Hg	205; 206	41 h.; 45 m.	(−); (−)
81 Tl	204; 206	5 m.; 97 m.	(−); (−)
82 Pb	209	3 h.	(−)
83 Bi			
88 Ra	229	1 m.	
89 Ac	231; 232; 233	12 m.; 42 h.; 3·5 h.	
90 Th	239 (233?)	28 m.	
91 Pa	233	2·5 m.	

TABLE 56 (*continued*)

Element and atomic number	*Radioactive isotopes*		
	Mass-numbers	*Half-value periods*†	*Particles emit*
92 U	236 ? ; 239	23 m. ; 10 s. and 40 s.	(−); (−)
93 Eka Re	239	2·2 m. and 16 m.	(−)
94 Eka Os	239	59 m. ; 17 h. and 5·7 h.	(−); (−)
95 Eka Ir	239	66 h.	(−)
96 Eka Pt	239	2·5 h.	(−)

† In connexion with this table, reference should be made to the mass-numb abundance of the stable isotopes given in Table 43, p. 182, as well as to the text o and to Fig. 40 (p. 121). See also Table 29, p. 116, which is restricted to ra isotopes produced by *neutron* bombardment. (−) = electron (β-ray); (+) = p s. = second; m. = minute; h. = hour; d. = day; y. = year.

TABLE 57

Constants frequently used in Radioactive Calculations

Velocity of Light $c = 2{\cdot}9978 \times 10^{10}$ cm./sec.

Planck's Constant $h = 6{\cdot}610 \times 10^{-27}$ erg sec.

Charge of Electron $e = 4{\cdot}800 \times 10^{-10}$ e.s.u. $= 1{\cdot}6012 \times 10^{-20}$ e.m.

Mass of Electron $m = 9{\cdot}105 \times 10^{-28}$ gm.

Mass of Hydrogen Atom $m_{\text{H}} = 1{\cdot}673 \times 10^{-24}$ gm.

Unit of Atomic Weight $m_1 = \dfrac{m_{\text{H}}}{1{\cdot}0081} = 1{\cdot}660 \times 10^{-24}$ gm.

$m_1 = 0{\cdot}93105 \times 10^9$ e.V. ; 1 e.V. $= 1{\cdot}0741 \times 10$

Atomic Weight in Chemical Scale = 0·99973 × Atomic Weight in Physical

Atomic Weight in Physical Scale = 1·00027 × Atomic Weight in Chemical

Gram-Molecular Volume (at N.T.P.) $v_0 = 2{\cdot}2414 \times 10^4$ c.c.

Loschmidt's Number (Avogadro's Number):

per mol $N = 6{\cdot}028 \times 10^{23}$;

per c.c. (at N.T.P.) $L = 2{\cdot}689 \times 10^{19}$ cm.$^{-3}$

Mass of 1 c.c. Hydrogen (at N.T.P.) $= 8{\cdot}987 \times 10^{-5}$ gm.;

Volume of 1 gm. Hydrogen (at N.T.P.) $= 1{\cdot}1127 \times 10^4$ c.c.

Mass of 1 c.c. Helium (at N.T.P.) $= 1{\cdot}785 \times 10^{-4}$ gm.;

Volume of 1 gm. Helium (at N.T.P.) $= 5{\cdot}6023 \times 10^3$ c.c.

1 Year $= 3{\cdot}65 \times 10^2$ days $= 8{\cdot}760 \times 10^3$ hours $= 5{\cdot}256 \times 10^5$ minutes
$= 3{\cdot}1536 \times 10^7$ second

1 Day $= 1{\cdot}44 \times 10^3$ minutes $= 8{\cdot}64 \times 10^4$ seconds.

$$e = 2{\cdot}71828; \quad \frac{1}{e} = 0{\cdot}36788; \quad \log_{10} e = 0{\cdot}43429; \quad \log_{10} x = 0{\cdot}43429 \log$$

$$\log_e 10 = \frac{1}{\log_{10} e} = 2{\cdot}30259; \quad \log_e x = 2{\cdot}30259 \log_{10} x.$$

$$\log_e 2 = 0{\cdot}69315; \quad \frac{1}{\log_e 2} = 1{\cdot}44270.$$

For Atomic Weights of the Elements see Table 43 (p. 182).

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